Optimising Manufacturing Industrial Production Layout for Occupational Health and Safety

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Abstract

Context – Historically, the focus of industrial health and safety (H&S) has been on safety and accident avoidance, with relatively less attention on long-term occupational health other than via health monitoring and surveillance. Multiple overlapping health consequences occur in industry workplaces that are difficult to separate, measure, and attribute to a source. Furthermore, many health problems occur later, not immediately on exposure, and may be cumulative.

Issues – Consequently, it is difficult to conclusively identify the cause of an H&S issue. Workers may lack knowledge of long-term consequences, and thus not use protective systems effectively. Compounding this, is the lack of instruments and methodologies to measure exposure to harm. The existing methodologies for calculating safety risk are based on the constructs of consequence and likelihood. However, this may not be appropriate for health, especially for long-term harm, as both the consequence and likelihood may be indeterminate.

The growth of companies introduces new challenges because production does not always scale linear, and organisational systems have to be extended. Manufacturers need to grow productivity, which requires capital investment and changes to the structure of their operational management systems. Making changes to an operational system not only changes productivity economics, but can have further impacts on occupational health and safety (OHS). This complexity arises because manufacturing operations can be nonlinear, and many H&S risks are difficult to manage. Identifying the risk is also difficult, especially measuring its corresponding likelihood and frequency. Methods do exist for production economics and OHS, namely plant simulation and risk assessment, respectively. However, they are applied disjointedly.

Need – There is a need to develop methods to simultaneously manage production economics and occupational health and safety risk.

Approach – We developed an instrument for managing OHS risk, namely DQL. The DQL was then integrated in the plant simulation using sub-model creation. This integration methodology was then applied to case studies for validation. We especially focused on small and medium enterprises in the manufacturing industry.

Results – Conceptual models for evaluating risk-taking activities of workers were created, namely RASH, and perverse agency. Diminished quality of life (DQL) was developed to measure the risk to H&S, and especially focused on long-term effects. The integration of DQL and plant simulation was accomplished using Arena software. This methodology was then applied to case studies for application and validation. Long-term health has been considered using conventional risk assessment, this was achieved through an integration with DQL.

Originality – This work has the potential to assist engineering economics and OHS, specifically in the complex investment mix of hardware and labour, and the concomitant effect of operations on societal outcomes as measured in H&S.

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Preface

This thesis is submitted for the degree of Doctor of Philosophy in Mechanical Engineering at the University of Canterbury.

Journal publications:

1. Ji, Z., Pons, D., Pearse, J. Why Do Workers Take Safety Risks?—A Conceptual Model for the Motivation Underpinning Perverse Agency. *Safety* 2018, *4*, 24. https://doi.org/10.3390/safety4020024
2. Ji, Z., Pons, D., Pearse, J. Measuring Industrial Health Using a Diminished Quality of Life Instrument. *Safety* 2018, 4, 55. https://doi.org/10.3390/safety4040055
3. Ji, Z., Pons, D., and Pearse, J., Plant system simulation for engineering training workshops. *Computer Application in Engineering Education*. 2019; 1–14. https://doi.org/10.1002/cae.22171

Presentations:

4. Ji, Z., Pons, D., ‘Occupational health in an industrial context—Overview of UC research project, NZSSE, IPENZ, Wellington, New Zealand, 25 January 2017

Glossary

Diminished quality of life (DQL):	A health and safety risk assessment methodology based on the concept of quality of life. DQL refers to the extent to which a hazard has a biological consequence that adversely affects a person's quality of life much later in life.
Engineering Economics	Also known as engineering economy, refers to application of economic principles in the analysis of engineering decisions.
Health:	Avoidance of long-term harm.
Perverse agency:	Activities (which are short cuts in OHS) that people try to do, and these activities are based on personal motivation, where they have the knowledge of the risk they may face.
Personal protective equipment (PPE):	Refers to protective clothing, helmets, goggles, or other garments or equipment designed to protect individuals from injury or infection.
Plant simulation:	Using models to develop data as a basis for managerial or technical decision-making in the area of plant industry. Also, it is the name of a proprietary software tool from Siemens.
Plant systems engineering:	Application of systems engineering to plant, with a specific focus on productivity, modelling/simulation, operator safety, maintenance.
Risk:	Risk is defined in several different ways. In this work, we adopt this definition: Risk is the potential of gaining or losing something of value.
Safety:	Prevent accidents that immediately cause harm.
Systems engineering:	Systems engineering (SE) is the application of engineering management, design methods, analysis tools, and testing protocols in a systematic and integrated manner, for the solution of complex engineering problems.
Treatment:	The use of an agency to deal with hazards.
WHODAS:	World Health Organization Disability Assessment Schedule

Contents

Chapter 1: Introduction

1.1 Overview

Managing occupational health and safety is an ongoing focus in industry workplaces [1]. Existing methodologies for managing occupational health and safety (OHS) risk are primarily focused on reducing the consequence of harm and likelihood of the occurrence [2, 3]. Historically, the main focus has been on the safety part, i.e. the prevention of accidents that might immediately lead to harm. However, there is little literature on managing health risk at work, especially the prevention of long-term injury, i.e. injury that only becomes apparent after a period of time, such as hearing loss, pneumoconiosis and nerve damage, back injury, and soft tissue injury. The issue with these injuries, is that they cannot always be attributed to a specific workplace accident. Given that workers change jobs, it is often not even possible to associate the source of the injury with a specific workplace. This is problematic because no one specific employer takes action to identify and prevent the injury.

Alternatively, from an economic perspective, it is difficult for workers to identify that they have ill-health or loss of function, and that this has an industrial cause, and consequently they may not qualify for health insurance cover. These two effects have led to a radical change in the ways that different countries approach Health and Safety (H&S). There has been a growing awareness of H&S at work, and a need for reducing accidents and long-term harm to health (especially the occupational health) of workers.

Additionally, to survive among the global manufacturing industrial competition, the manufacturing industry is trending towards lean, agile and effective. Optimisation in manufacturing industrial production layout is one of the ways to achieve this objective production, and it is affected by multiple attributes, such as construction environment and manufacturing workflow. Attributes are also associated with the system's performance, and every single change in the operation can have a positive/negative impact on production economics. Industry professionals now use plant simulation to manage economic outcomes and production layout [6]. However, there are no holistic methods for industry professionals to simultaneously consider industry economic outcomes and OHS risks.

Therefore, the main purpose of the thesis is to develop a quantitative methodology to manage OHS and simultaneously optimise production economics via plant simulation methodology. Presenting OHS risk via a quantitative and virtualised simulation model brings benefit to managing risk, especially when dealing with residual risk. Additionally, long-term health risk is considered in this thesis, which is managed by DQL methodology. Methodologies that have been applied to this thesis are, for example, OHS risk management, quality of life, decision making, ontology, process systems engineering, computational modelling, discrete event simulation, and Monte Carlo sampling.

1.2 Aims of the Work

Existing approaches for managing OHS are focused exclusively on the risk management [4]. Within that framework [4], the general focus is on safety accidents [5]. The area of health is weakly handled. Thus, there is a need to more explicitly include health aspects in risk assessment methods.

Alternatively, plant simulation is a platform which uses mathematical models to represent operation process and was developed based on discrete event theory. Plant simulation allows professionals to analyse system performance [6]. Plant simulation has been used to increase productivity, improve machine utilisation, and reduce waste through evaluating production implementations [7, 8]. However, health and safety aspects are considered extremely little in plant simulation. Thus, there is also a need to develop a holistic method which integrates health and safety and plant simulation.

Complexity arises when modelling the operation process in the content of manufacturing [7, 9], this is because a manufacturing system is not always scaled linearly. Furthermore, many manufacturing processes become lean and agile, hence also increasing the difficulties. Another difficulty is that the existing research associated with plant simulation has been largely focused on production economics and is quantitative, however qualitative methodologies have been majorly applied to measure OHS risk. Additionally, there is little commonality between these methods. Likewise, risk assessment methods do no address productivity. Therefore, finding a way to conduct these differences between OHS risk and plant simulation is difficult.

Therefore, the aim of this thesis is to develop a methodology which integrates OHS, risk assessment, and plant simulation, with a particular focus on representing the long-term health risks and production economics.

1.3 Organisation of the Thesis

The thesis is delivered in the following nine Chapters. The connections between each chapter is indicated in Figure 1.1.

Chapter 1 provides an introduction of the thesis, this contains an overview and the aims of the research.

Chapter 2 presents the literature review of risk management, OHS, biological consequences, and plant simulation. This then followed by evaluating the gaps between the body of knowledge and addressing the complexities.

Chapter 3 presents the methodology and also identifies the purpose and the complexity of this research.

Chapter 4 to Chapter 8 contain the results. Chapter 4 describes a conceptual model, namely the 'RASH' model, which illustrates a person's decision making when they are associated with H&S risks. This chapter develops a theoretical model to indicate the reason why workers voluntarily expose themselves to OHS hazards.

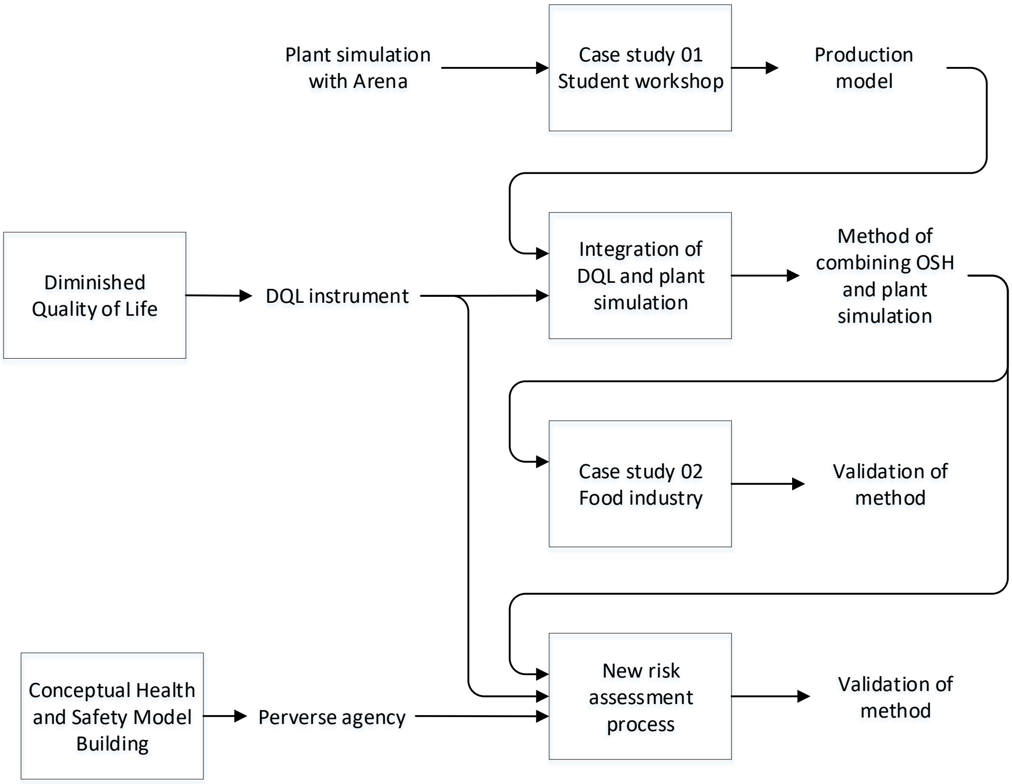

Figure 1.1: Organisation of the thesis

Chapter 5 explores a quantitative method to measure OHS, hence Diminished Quality of Life (DQL). The principles are based on identifying the frequency of hazard exposure, likelihood of an injury, and level of harm of the biological consequences using the World Health Organization Disability Assessment Schedule (WHODAS) 12-item inventory. This results in an overall metric of risk for the activity, which is called the Diminished Quality of Life score. This may then contribute to risk prevention treatments. In this way, a method has been devised to evaluate long-latency harm, cumulative effects, and chronic injuries.

Chapter 6 describes a methodology which optimises the productivity of an engineering workshop, for the unusual class of situations where the product moving through the simulation is not merely a physical product, as in conventional simulation approaches, but rather the combination of people (students) and their partially completed physical product. This is valuable for us in the next step of the research, hence to integrate risk management with plant simulation.

Chapter 7 develops a methodology 'plant safety simulation' (PSS) which integrates risk management with plant simulation. This is achieved by designing a *DQL routine* in the simulation, which includes programming attributes, decisions, and assign models. The results can be used to identify the hazards at work. This can then also help H&S representatives to create a comprehensive hazard management system. This integration methodology creates the opportunity for industry people to manage multiple objectives at the same time, for example, safety risk and production economics.

Chapter 8 develops a methodology which has the potential to provide a novel integrated approach to assist the management of production economics and H&S risk. This work has a consideration to optimise production economics in the complex investment mix of hardware and labour, and the concomitant effect of operations on societal outcomes as measured in H&S. H&S risks here were determined in a quantitative manner, which may help in further risk management, especially in non-notifiable risks and residual risks. The integration of risk management and production economics may further help SMEs grow in a sustainable way. It also validated the methodology that we presented in Chapter 7.

Chapter 9 develops a methodology which integrates DQL with conventional risk assessment. A new risk matrix was presented, based on likelihood of harm and level of consequence determined by WHODAS.

Chapter 10 delivers an overall discussion of implications, limitations, and future research.

Chapter 11 presents the conclusion of the thesis.

There are four appendices attached to this thesis. Appendix A addresses the co-authorship of publications. Appendix B shows the instruments of DQL. Appendix C delivers plant simulation programmes. Appendix D presents the ethics approval for the case study.

Chapter 2: Literature Review

The objective of this work was to develop a methodology which integrates OHS and plant simulation to simultaneously manage OHS risk and engineering economics. The literature review is targeting to examine the existing research.

Keywords were used to guide the literature review, *occupational health and safety*, *risk assessment*, *safety motivation, safety agency, organisational safety*, *manufacturing industry*, *modelling and simulation*, *operations management*, *systems engineering*, and *engineering economics*. Based on the intervention of the study, we classified the literature into three aspects, namely: OHS, risk management, and system engineering.

2.1 Health and Safety

2.1.1 Occupational Health and Safety in Manufacturing Industry Work

Historically, the main focus of OHS has been on safety, rather than the health aspects. The importance of OHS has changed during recent years, with an increased emphasis on the responsibility of the industry to avoid harm to workers.

Safety here refers to a prevention of accidents that might immediately lead to harm. In contrast, health refers to long-latency health issues, cumulative harm effects, or chronic harm. The issue is that occupational harm cannot always be attributed to a single or definitive accident, and does not always occur immediately after an event. Unlike an accident, this type of harm may take time to become apparent. There may be delayed onset or persistent symptoms over extended periods. Additionally, some health issues may occur by cumulative hazard exposure [10]. In contrast, the safety perspective is more focused on the immediate harm consequences of accidents.

The World Health Organisation (WHO) describes occupational health and safety as:

> Occupational health deals with all aspects of health and safety in the workplace and it has a strong focus on the primary prevention of hazards. The health of the workers has several determinants, including risk factors at the workplace leading to cancers, accidents, musculoskeletal diseases, respiratory diseases, hearing loss, circulatory diseases, stress related disorders, and communicable diseases, as well as others. Employment and working conditions in the formal or informal economy embrace other important determinants, including working hours, salary, workplace policies concerning maternity leave, health promotion, and protection provisions, etc. [11].

Some common OHS hazards in the manufacturing industries are, for example, noise [12], hit by foreign objects [13], dust inhalation [14, 15], chemical exposure [16], and repetitive activities [17, 18]. Noise at high levels is an example of an insidious health hazard because of the potential for workers to be exposed over long durations. This can result in hearing loss, which can be a permanent injury [19]. WorkSafe New Zealand showed that there were more than 11,000 ear injuries reported in 2014 and most of them were noise-related hearing loss

[20]. Most nations are aware of noise and use enforcement, standards, and legislation to avoid workers suffering hearing loss [19].

Hazards in H&S are defined as “a source or a situation with a potential for harm in terms of human injury or ill-health, damage to property, damage to the environment, or a combination of these” [21]. Individuals have the right to work in a place with a healthy and safe environment, and this is especially so for people working in manufacturing. Workers in manufacturing are exposed to relatively high risks, such as breathing dust [14, 15], contact with toxic and poisonous products [16, 22], and participating in repetitive activities [23, 24]. These hazards can result in injuries and illness [25].

Many health problems are not immediately evident in the response of the human body. Some health problems can be affected by the work environment [26], e.g., chemical [27, 28], light [29], temperature [30], fire [31], and noise [32]. Existing research shows that poor environmental conditions were common in the manufacturing industry, and there were little to no ergonomics employed at workplaces [33]. Other health issues are related to physical [23, 24] and psychological effects [34]. Hence the biological consequence corresponding these issues are largely chronic. For example, poor ergonomic design workstation can have negative effects on a worker’s musculoskeletal system [35, 36], and may further result in muscle fatigue [37] and musculoskeletal disease [38].

In contrast, safety accidents cause immediate harm to the human body. Safety hazards in manufacturing typically occur when working with tools, machines, materials, and transport vehicles [39]. Some research has addressed the typical machinery hazards, such as cutting, crushing, and squashing [40], electrical shock [41], and radiation [42]. Other research has indicated that accidents can be caused by the work environment, such as uneven surfaces [43].

Many prevention and recovery solutions for H&S have been developed [44]. For example, personal protective equipment (PPE) is widely used to protect the human body [26]. Many studies have focused on developing new protection equipment [45, 46], traffic routes [47], safety regulations [48, 49], managerial policies [50], and safety climates [51].

2.1.2 Motivation

Returning to the WHO definition of OHS above, it is apparent that, in the conventional construct, the causal factors are predominately external constraints of the workplace that are imposed on the worker, and there is little explicit identification of motivations internal to the workers themselves. However, motivation is an important factor in occupational health and safety.

Motivation is a psychological concept and it is used to describe the reason for a person’s behaviour. Expectancy theory is a motivation theory developed by Victor H. Vroom in 1964 [52]. Expectancy theory explains motivation as the combined effect of a chain of three factors: expectancy, instrumentality, and valence [53]. This is typically expressed as:

$$\text{Motivation} = \text{Expectancy} \times \text{Instrumentality} \times \text{Valence}$$

Expectancy is the personal assessment that exertion of effort will result in performance. Instrumentality represents the personal thinking of whether that performance will result in reward or punishment. Valence describes the extent to which that reward or punishment is important to the person. If the outcome of the motivation is positive, it means that people are happy to do the job.

There are two types of rewards that are used in driving employee's motivation: intrinsic and extrinsic rewards [54]. Intrinsic rewards are psychological rewards, such as verbal rewards or a sense of accomplishment [55, 56]. Extrinsic rewards are rewards such as money, bonuses, holidays, and promotions [54]. Employers select rewards to deliberately drive motivation. This is a widely researched area in the business motivation literature, where the objective is to better understand the relationship between rewards and performance, e.g. [57]. Many industries use this method to drive employees' motivation and increase productivity [58], participation [59], and quality of work [60]. However, the same motivational methods may cause workers to over-align with organisational purpose, and they result in stress and fatigue, and hence, increase their risk of harm. Therefore, psychosocial factors are also important at work [61].

2.1.3 Mental Health and Motivation

Mental health is another considerable issue for the industry. It is described as the "psychological state of someone who is functioning at a satisfactory level of emotional and behavioural adjustment" [62]. Mental health problems have negative effects on individual motivation [63] with real economic consequences, such as decreased productivity. Contributory factors include time pressure, job satisfaction, and workload [34]. Modern legislative frameworks explicitly assign to industry the duty to protect both physical and mental health, e.g. [64], but the safety frameworks are asymmetrically focused on the former.

Existing research in mental health in the context of safety is focused on mental workload [65], effects between mental capacity and work ability [66], loss of concentration and difficulty in cooperating [67], physical behaviour outcomes [68], and links to accidents [69, 70].

There is a strong relationship between mental health and an individual's motivation [71, 72]. In turn, motivation affects people's decision-making [73]. The present paper focuses on motivation, and how it affects workers' approaches to safety. Mental health is not explicitly included here, except as a possible precursor to motivation.

2.1.4 Causes of Voluntary Exposure to Risk

Lack of OHS knowledge can increase the likelihood of exposure. Some workers do not clearly understand the risks associated with a task, and they cannot anticipate the hazard beforehand. Therefore, it is usually too late for them to devise a treatment or precaution when they notice the harm occurring [74]. Workers with a high OHS awareness are likely to pay more attention to their health and safety, and this makes them more careful at work than other people [75].

Secondly, some experienced workers have a good understanding of the occupation health and safety, but they still accept work with risks and they tacitly consent to unknown safety hazards. Survey results show that 90% of workers are not afraid to meet challenges at work, even though they know that it will be an unsafe environment or unsafe work practices [75].

It is apparent that workers are willingly or inadvertently taking short cuts in their health and safety.

Thirdly, management and organisational culture can affect OHS hazard exposure [76]. The reason for an organisation existing is to make a profit, and this has a strong connection to production targets in manufacturing industries. Organisations have to meet their productivity targets, thus they provide incentives for workers to align with economic objectives. The common methods using in labour-productivity improvement are overtime work and imposing pressure on workers [77]. Consequently, workers have to sacrifice their rest time or increase their productivity, which makes them feel tired, unbalanced, and stressed [78]. Providing rewards is one of the treatments to drive workers' motivation [79, 80]. However, it still increases the risk of OHS hazards at work [77]. Therefore, it is easy to make changes in workers' motivation, but this can also leave them feeling anxious or upset.

Poor managerial ethics also has a negative effect on safety and accident prevention [81]. This may be because some managers cannot identify the OHS problem clearly, simply telling their employees that they are working within a safe situation, and prevent them from questioning the organisation's decisions [82]. Furthermore, organisational culture plays an important role in workers' attitudes [83]. This is because of group mentality. This causes a person to behave in a way that is based on others' performance rather than their own [84]. It operates via psychology mechanisms of peer pressure and vicarious learning. Cultures that emphasise manly behaviour may, for example, cause workers to avoid wearing ear protection if they feel that it makes them look soft. It is difficult to make changes in workers' perceptions and attitudes about standard safety practices [85].

2.1.5 Contemporary Issues in Occupational Health and Safety (OHS) Research

There are many ongoing issues with OHS as applied to industrial work. Firstly, the literature identifies only a few methodologies to measure health and safety. Most of the research is focused on risk reduction and a limited range of interventions (for example, educating workers and personal protective equipment (PPE)). Secondly, H&S legislation in many countries require employers to minimise occupational health loss, e.g. [64], however the long latency of these injuries makes it difficult to detect the damage as it occurs. Additionally, it is difficult to determine which past work period contributed to the harm, and as a result, it is difficult to prevent. Thirdly, causality is unknown. There is only limited understanding of the causality for occupational health issues. Workers typically undertake many different activities in manufacturing plants, so it is difficult to attribute harm to a specific cause. Furthermore, it is also difficult to understand why people take short cut actions in health and safety. Fourthly, most of the attention relating to risk assessment is applied to the safety and the prevention of accidents that lead to immediate harm, with less focus on health issues, especially on long-term health. A related problem is that the definitions and methods in monitoring health risks are limited. Finally, qualitative methodologies were largely applied to OHS research and most OHS risk methodologies are depending on subjective assessment where deviations may occur. This becomes inefficient when dealing with long-term health issues and residual risks.

2.2 Risk Management

2.2.1 Risk Management of ISO31000

Risk is defined in several different ways. The thesis here defines risk as: the potential of gaining or losing something of value [86]. Risk management plays an important role in management; methodologies such as fault tree analysis (FTA), bowtie analysis, failure mode and effects analysis (FMEA) are widely used [87]. Businesses of any size and background need to be better managed in risk during their work lifetime. Any kinds of internal or external factors can make uncertain influences to objectives and further result in risk exposure [4].

The risk management standardisation ISO31000 was published in 2009. ISO31000 illustrated a workflow of risk assessment, which contributed to building a sustainable environment for managing risk. ISO31000 has been applied to many areas, for example, product design [88]. The workflow of risk assessment is shown in Figure 2.1. ISO31000 provided a way to improve the communication between each stages. It also gains the credibility of risk identification, analysis, and evaluation.

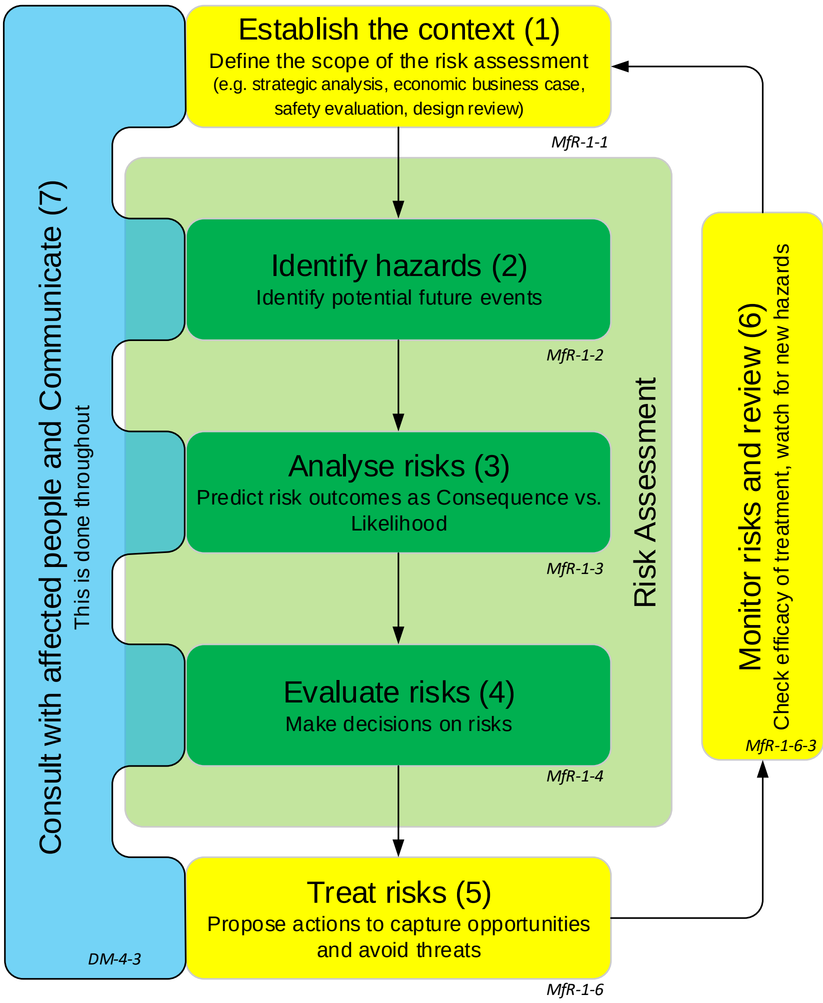

Figure 2.1: Risk Assessment Process per ISO31000 (2009). Image D Pons, reproduced by permission.

AS/NZS 4360:2004 is the old version standardisation of risk assessment before ISO31000 and carried out by NZ government in 2004. Compared with AS/NZS 4360:2004, ISO31000 provides improvements in many aspects, such as increasing likelihood of achieving objectives, encouraging proactive management, and the identifying of opportunities and threats.

2.2.2 Risk Management in Occupational Health and Safety

Historically, the general focus of OHS has been on preventing safety accidents, e.g. machinery accidents and human error [89]. Existing approaches to reduce health and safety risk are primarily focused on risk management methodology [21]. ISO 31000:2009 presents a systemic workflow process for general risk assessment [90], which finds application in many industries [91, 92]. Many countries are focused on establishing general principles for the protection of individual health and safety at work, for example, the European Union Directive 89/391/EEC [93] and New Zealand Health and Safety Work Act [64]. Research on health risk management is focused on work policy [94], the working environment [95] [96], risk prevention [97, 98], and risk estimation [86, 99]. Some research has focused on design aids to identify hazards, e.g. inspection checklists [100, 101]. Some other approaches are focused exclusively on the risk management methodology [4], such as the continual improvement circle [25], fault tree [102], and safety matrix [103]. Other important developments in health and safety research have been to better address the mental health component of work, e.g. psychosocial risk management [104, 105] and mental health [106], and provide means for these factors to be included in the design of safe systems of work. Another area where psychology intersects with health and safety, is in the perverse agency concept [107], which seeks to explain why workers take safety risks that may lead to adverse long-term health.

The area of health is weakly handled by the standard approach to risk management. The level of harm associated with health issues is difficult to determine [108]. The actual cause of harm is often difficult to determine and, consequently, this results in a weak estimate in the level of harm [109] and corresponding treatments. Many risk methodologies are based on estimates with consequences [110] [111],[112], and this is difficult to determine in a chronic health case, as the biological consequences are seldom immediately apparent after exposure.

Quality of Life Scales (QOLS) have been developed in the medical area and used to quantify the effects of disability, age, and health impairment [113]. Several scales and instruments have been developed based on this methodology, e.g. WHODAS [114], World Health Organization Quality of Life (WHOQOL-BREF) [115] and RAND-36 [116]. These ask questions about the ability of individuals to undertake tasks of daily living [117]. These instruments have also been applied to mental, neurological, and addictive disorders [118].

2.2.3 Plant H&S and Hazard Assessment

Individuals have the right to work in a place with a healthy and safe environment, especially working in a manufacturing plant. Workers have to face high occupational health risk every day, such as breathing dust or touching toxic or poisonous goods [119]. Some other hazards are associated with human error and the work environment [120]. In order to minimise those risks and avoid harm, employers and workers should pay more attention to workplace health and safety. A well-being focused working environment begins with a good understanding and reasonable identifying what health and safety risks are, especially those have potential may cause injuries and illness [25].

"Industrial manufacturing plant presents numerous safety threats. Generally, these can be categorised into hazards that are intrinsic to the individual plant, and those due to integration of the plant into a system [121]:

1. Hazards due to construction, fabrication, commissioning, and decommissioning machines or plant.
2. Hazards those are intrinsic to specific machines.
3. People using the machine in the wrong way: human error.
4. Hazards due to the interaction between machines. Note that plant environments are mostly systems engineering applications, i.e. there are a large number of bought-out pieces of equipment of external design and fabrication. There are new risks that occur in the way the equipment is integrated together.
5. Risks caused by the higher-level control system, e.g. supervisory control and data acquisition (SCADA) that controls multiple machines."

Safety management system (SMS) has been employed to manage activities performance and analyse H&S hazards. Many industry companies are coming to realise that SMS is an effective way to keep workers safe and reduce corporate costs [122].

Hazards assessment based on H&S includes identifying risks from internal and external sources. Then calculating and evaluating their likelihood and consequence [123]. Each plant system has a specific production workflow and different work environment, which makes every production system becoming unique. This particularity makes H&S hazards becoming diversification.

2.2.4 Contemporary Issues in Health and Safety Risk Research

The research literature is sparse on methodologies for assessing health risk in the industry. The majority of safety research is focused on risk reduction and accident prevention, rather than biological consequences. Methods to evaluate long-term health effects are especially absent. Self-prevention is difficult because of the challenge of identifying harm associated with the work, see also the concept of perverse agency [107]. The relationship between hazards and consequences are often poorly developed. There has been little emphasis on health in the workplace and, consequently, prevention and treatment are poorly addressed. There are considerable difficulties in associating the source of injuries with a specific workplace because of worker mobility. This is problematic because no one specific employer acts to identify and prevent the injury, especially long-term health effects.

Some existing approaches to reduction of H&S harm are focussed exclusively on the risk management methodology [4], such as continuous improvement circle [25], fault tree [102] and safety matrix [103]. Other methods use computer-based simulation for process hazards identification [124] [22], it also gains the reachability examinations of dangerous plant states with the method of computer-based technology. Within that framework, the general focus is on accidents and the safety part, e.g. [5]. However, the area of health is weakly handled by these standard approaches, especially the occupational health. Almost all of the plant hazard simulations with productivity-optimisation works are done without considering health and safety issues [125]. Thus, there is a need to do more work to explicitly include health aspects in risk assessment methods.

2.3 Systems Engineering and Plant Simulation

2.3.1 Systems Engineering

Systems engineering (SE) applies to many aspects of engineering, for example, aircraft systems [126], manufacturing systems [127] and chemical products [128]. A typical definition of systems engineering (SE) is that it is "the application of engineering management, design methods, analysis tools, and testing protocols in a systematic and integrated manner, for the solution of complex engineering problems" [121].

Plant systems engineering (PSE) is the application of systems engineering to a plant, with a specific focus on productivity, process-time management, and work procedures [3, 129]. PSE is also concerned with flexibility, sustainability, and efficiency [130], and finds applications in many industries [131]. Previous research has focused on production planning [132], system design [133], productivity improvement [134], and physical product design [135]. Other associated studies include business process management [136] [137], and risk management [138] [139].

2.3.2 Plant System Simulation

"Simulation refers to a broad collection of methods and applications to mimic the behaviour of real systems, usually on a computer with appropriate software" [140]. A plant system simulation (PSS) follows mathematical rules and results in numerical outcomes which imitate the simulated system's characteristics [141]. PSS is a method that uses simulation methodology to analyse plant systems. Early simulation consisted of random number generators, equations, and random process routines [142]. Today, many simulations are based on continuous variables and probability distributions, some others are based on discrete event simulation (DES) [143]. Many simulations now provide interchangeable templates, graphic animations and detailed result outcomes, which are useful in evaluation [144]

Plant system simulation has been used in the field of business management [144], manufacturing [145-147], medical systems [148], construction [149], traffic [150] and logistics [151]. Many PSS research focused on managing machine utilisation [152, 153], productivity capacity [153] [154], waste [155-158], schedule planning [159], work efficiency [145], and work in process (WIP) [160].

2.3.3 Simulation in Plant Systems

In recent years, plant simulations have increasingly been used to support and monitor plant system design and operation [135]. Plant simulation is a powerful technology, which allows individuals to make wise decisions with evidence while solving complex problems. Many studies have found that optimising production economics were achieved using plant simulation methodology [6, 9]. Plant systems are complex and consist of many objectives, e.g. machine arrangement, productivity, and production target. Plant simulation provides an integrated framework for these objectives and with variety of applications such as manufacturing, construction, and chemistry [6].

Many plant simulations were developed based on discrete event simulation. Simulations are programmed through using model languages in software such as ARENA to describe operational process activities, e.g. welding, installation and maintenance. It is widely used in the area of manufacture, transportation and logistics. Plant simulation technology has performed well in solving complex problems to enhance companies' competitiveness by decreasing bottlenecks, avoiding waste, minimising total cost, and increasing productivity [7].

Plant simulation has the following advantages：

- Improves decision making with minimal cost;
- Compress and expand time (allows the speeding up or slowing down of specified conditions)；
- Reasons behind specific system conditions;
- Explores possibilities with minimal expenses;
- Diagnoses problems (understand the complex interactions between elements of the system);
- Identifies system constraints and limitations;
- Develops a general understanding of the behaviour of the system.

A simple plant may have a set layout, and this makes some simulation easier. Complexity arises when the layout is changing during the production [154]. Typical example is using portable equipment or portable workstations, or where the product mix is very variable from day to day. This is a common issue in lean and agile manufacturing.

Furthermore, many experiments not using plant simulation to improve production economics are requiring a large number of input variables, which physical experiment performance finds almost impossible to achieve. Therefore "plant simulation is utilised as a powerful and useful tool with which experimental trials could be conducted in a low-cost and reliable environment" [161].

There are more than 290 papers on plant simulation. Plant simulation has become a successfully adopted method in systems engineering, leading to increased interest in this research topic [6]. Plant simulations have been used to integrate other methods to solve complex problems in the recent decades as well. Typical applications include beverage production [162], flexible manufacturing systems [163], construction process productivity [161], supply chain management and transport systems engineering [164]. Some other applications using plant simulation methods are to reduce waste [164] and environmental harm [165].

2.3.4 Existing Simulation Tools

There are many simulation tools available in the area of plant simulation, for example, Plant Simulation, Arena, SIMUL8 and WITNESS [166]. This plant simulation software is used in many research areas, e.g. resource utilisation and machine arrangement.

(1) Plant Simulation:

Plant Simulation [167] software was developed based on discrete-event simulation (DES) by Siemens Company. It can model the operational processes to support systems performance analysis.

(2) Arena:

Arena is a simulation software designed by Rockwell Company. It provides an integrated framework for building simulation models in a wide variety of applications. It integrates all the functions needed for a successful simulation, including: (a) Animation; (b) Data analysis; and (c) Model verification. Arena is widely used in many comprehensive environments. Applications were found in productivity improvement [7] and waiting time reduction [162] [164].

(3) Simul8:

Simul8 software is a product of Simul8 Cooperation used for systems engineering. Applications were found in manufacturing, supply chain and health care. Simul8 allows users to build their own system with input data and logistic expression [168].

(4) Jack & Process Human:

Jack & Process Human simulation [169] is a tool for analysing human injury at operation. It has a special focus on ergonomics analysis. It is used to identify the hazards and corresponding consequences via simulating operation activities. 3D simulation is also available in Jack & Process Human software.

2.4 Gaps between Occupational Health and Safety, Safety Assessment, and Plant Simulation

2.4.1 Existing approaches between each aspect

A. Existing approaches in risk management and occupational health & safety

Existing approaches weakly handle the occupational health aspect, especially using quantitative methodologies. Existing methodologies for quantitative risk measurement are based on the subjective estimation of consequence and likelihood, which might result in deviation between different people. Applications were found in the area of coal mining [170], chemical [27], agriculture [171], industrial [172], food manufacturing [173], and construction [174]. However, the closest that anyone has developed a methodology combining risk management and occupational health, is Holmes' research in 1999. They made an exploratory study in small construction companies considering long-term disease, e.g. skins disease, and immediate injury (e.g. fall from height) [174, 175]. However, the biological consequences are not comprehensively addressed. Surveys and interviews were used in Holmes' research for data collection to address "why workers do not believe that occupational diseases can occur to them in their everyday work environment such as skins diseases" [174].

B. Existing approaches in risk assessment and plant simulation

Research associated with risk assessment and mathematical modelling and simulation were developed for many years, and applications were found in the area of manufacturing, chemical [124], and transport [176]. Risk assessment becomes effective using computer simulation. Largely adoptions were found to assist industry professionals in decision-making [177]. However, the integration with risk is not well-considered in the literature.

C. Existing approaches in Occupational Health & Safety and plant simulation

Research in the area of OHS management is well developed [178]. Many research studies were associated with hazard identification and risk analysis [178-182]. However, the literature for the integration of OHS and plant simulation is sparse. Zulch and Grieger designed the closest research relative to this research area [183]. Their research was funded by a German institute as a two-year project and named "Object-oriented Modelling of Planning and Management tasks in the Area of OHS". A 3D Visual digital factory software and ADAMO (OHS modeller) to analysis ergonomics and OHS for digital factories was created. They selected factors (e.g. noise) to monitor OHS in a single work process. The factors they monitored include light, noise and climate (temperature). The limitation of their simulation is that they were mostly focused on stations but not human operators.

There is little to no integration in the literature between plant simulation and industrial safety. The two are commonly treated as independent activities, which is odd given that the human operators are common to both. The limited work at the intersection of these fields is summarised as follows:

There have been many applications of modelling of safety outcomes. For example real time and mathematical models have previously been applied to estimate industry accidents [184]. Decision making relating to safety actions and team training have been developed based on Immersive Virtual Environments [185]. Computer-based simulation methodologies were also applied to safety training [186]. Explicit representation of plant operation was identified for managing complex working processes [187]. The relationship between person-related factors (e.g. risky decision-making, control beliefs, and general mental abilities) and their probability of violation in a production context were investigated, using factorial experimental design methodology [188].

As this shows, the intersection of the two fields is incomplete. There is at present no methodology to include safety risk considerations inside plant simulation models.

D. Existing approaches in engineering economics and OHS

Existing research illustrates that OHS needs to be considered while managing engineering economics; e.g. cost and benefit [189], and productivity [190]. Cost-benefit analysis was developed to measure the impacts of work accidents regarding OHS from both the company and society's perspective [191]. Some research was conducted to analyse the relationship between employee health investment and their attitudes, motivations, and behaviours at work [192]. Safety decision-making at organisation level was discussed with an integration of Monte Carlo and environment health and safety (EHS). Scenarios with different safety standards were considered for different investment situations [193]. The economic cost of occupational accidents was examined to illustrate the important relationship between income, productivity, and accident prevention [194]. Task-level productivity and physical strain were developed to value and improve productivity, H&S and quality of work in the construction industry [195]. Other research considered OHS and engineering management methodologies, for example, in the area of airliner maintenance strategy [196], lean [197], and inventory management [198].

In conclusion, sufficient work is associated with OHS and engineering economics, however, the focus has been mostly on accidents. The long-term health and engineering economics considerations are disjointed and insufficient.

2.4.2 Summary

As occupational health and safety gains importance in individuals' work lives, there is a need from an engineering perspective to consider OHS associated with production economics [6]. However, most works associated with production economics and OHS risk are disjointed.

Additionally, many OHS assessment are quantitative, hence complexity arises when measuring long-term health and its corresponding consequences. This becomes more difficult when measuring the residual risk. Hence, there is also a need to develop a quantitative methodology to measuring OHS risk, particularly for long-term health issues.

The following gaps were found in the literature:

- Methodologies do exist of optimising production economics and OHS, but these are poorly integrated.
- The existing methodologies for calculating safety risk are based on the construct of consequence and likelihood. However, this may not be appropriate for health, especially for the long-term harm, as both the consequence and likelihood may be indeterminate.
- The relationship between hazards and consequences is often poorly developed. There has been little emphasis on health in the workplace and, consequently, prevention and treatment are poorly addressed.
- There is little literature on developing methodologies to optimise safety, especially on long-term health issues, but this is limited to simple applications and a limited range of interventions (for example, educating workers and PPE).
- A WHO classification system exists for occupational health diseases in the form of the ICD-10NF, and functional disability by the ICF. However, these classifications are primarily used for statistical data collection in medical research. There is no evidence of them being applied in the industrial context in a coherent manner.
- Quality of Life Scale (QOLS) is a potentially valuable methodology to calculate the effect of harm on a person's quality of life and satisfaction. However, the QOLS methodology has not been applied or integrated into plant simulation in the industrial context.

- H&S laws require employers to minimise occupational health loss, however the long-term nature of these injuries makes it difficult to detect the damage as it occurs. Also, it is difficult to determine which past work period contributed to the harm.

Chapter 3: Methodology

3.1 Research Purpose

The thesis' objective was to develop a methodology to manage OHS risk alongside production economics. This was worth attempting for the benefit of being able to simultaneously consider and optimise the economic and health factors when designing plant layout. The methodology integrates occupational health and safety, risk management and plant simulation (see Figure 3.1).

The originality of the thesis is the development of a new method to integrate occupational health and safety with plant simulation. Another contribution is to develop and validate a risk-measuring instrument for occupational health and safety with a special focused on long-term health issues. The area under examination is New Zealand manufacturing organisations.

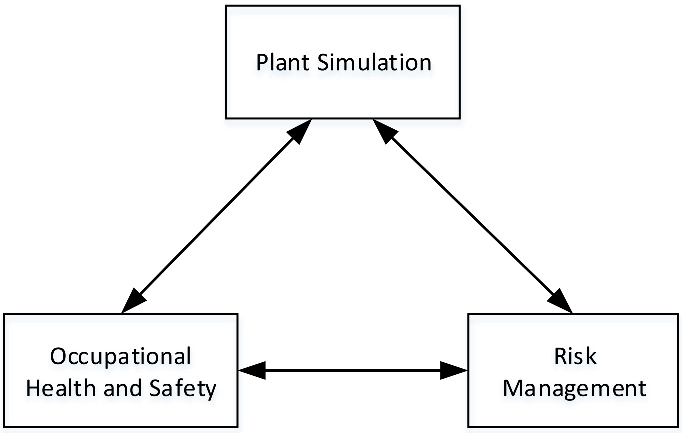

Figure 3.1: Integration objective

3.2 Complexity of the Research

Methods do exist for managing OHS risk, namely risk assessment and quality of life; as well as many methods for production, e.g. lean, theory of consistence, and minimising waiting in queue. However, they are applied disjointedly. Complexity in our research arises because:

- Occupational health effects are difficult to predict due to their long-term development post-exposure.
- It is also difficult to identify which specific work activity or employment period caused the OHS harm.
- The measurements of OHS harm are qualitative, whereas plant simulation is based on quantitative variables.
- Modelling manufacturing systems is a complex process because manufacturing production does not scale linearly. It is difficult to monitor these multiple parameters (OHS risks) among common factors (such as utilisation, capability).
- Finding a way to integrate OHS risk and production economics into a holistic decision-framework is non-trivial and has not been demonstrated.

3.3 Research Approach

The approach of the thesis is shown in Figure 3.2. Firstly, the thesis focuses on building a conceptual model which identifies how a person makes risky decisions in the workplace. The second step was to determine the hazards in the workplace and identify the corresponding consequences in the literature. Long-term health consequences are a special focus. Then a risk-measuring instrument was developed based on DQL. This instrument was validated via a case study in an engineering workshop. We then integrate the DQL methodology into simulation. This is followed two steps: (a) Building a simulation based on discrete-event simulation. This was a case study. The initial aim was to discover whether it is possible to connect DQL with plant simulation. (b) The second step was to apply this integration to an industry case study. We then integrate DQL methodology with conventional risk assessment. This is to assist the building of a mechanism for H&S risk measurement. A new risk matrix, thresholds and corresponding response activities were developed with a special focus on long-term health issues.

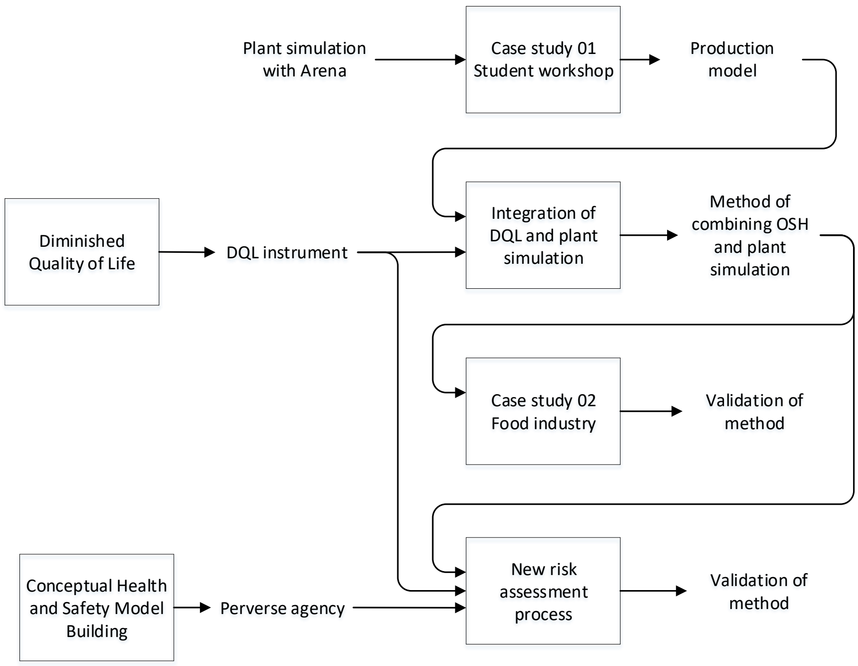

Figure 3.2: Approach

The integration of DQL involves simulation modelling. Several software programs (e.g. Plant Simulation, Witness, Simul8, and Palisade decision tools) were examined with a view towards an integration of the DQL concept. Arena was selected for the following reasons:

- Arena employs a flowchart modelling methodology which is similar to the manufacturing process. DQL variability can be managed using statistical distributions via the assignment model.
- Simulation of paths and routes can be adopted to manage hazards routine. This is also favourable for integrating the DQL concept.
- The statistical capability was able to represent the DQL risk and engineering economics.

The detailed methodologies used, and their sequence are shown below.

3.3.1 Conceptual Health and Safety Model Building

The purpose of this step was to develop a model to explain the causality whereby people take shortcuts in personal OHS. We wished to understand the human factors and the flow of conscious and subconscious decision-making that affect hazards exposure.

A qualitative methodology was applied to develop the model. We started by examining the literature for relevant constructs in the OHS literature. We then developed an initial model that sought to describe how workers' motivation affects their actions. This was presented to the annual general meeting of the New Zealand Society of Safety Engineering [199] and discussed by a group of eight professional engineers with expertise in safety engineering. They provided a critique of the model, identifying areas that were well-represented and also those that were underrepresented. From this early work arose the idea of perverse agency (described below). These discussions were used by the authors to further refine the model.

Subsequently, there was an individual discussion with an engineer from a construction firm, and this resulted in further refinements. We then examined the Pike River Mine disaster [62], from which we extracted additional principles of how incentivisation could affect workers' motivation towards unsafe acts. From this arose an element in the model relating to being over-aligned with organisational purpose.

The next stage in the development of the model was the adoption of several constructs from psychology and organisational behaviour, e.g. personality, dark triad, and motivation theory. Doing this grounds the model in the wider literature. The psychological constructs themselves are not critically evaluated here; rather, it is the integration of them into a wider model that is new. Consequently, the constructs are defined at first usage in the results, rather than being described in the literature review above.

Moving to completion, we then developed the model to explain why workers might appear to willingly forgo their own safety to complete a task. Throughout the development, we applied a systems engineering methodology. Specifically, we represented the ideas as a flowchart with proposed causal mechanisms, and we continuously revised it to ensure coherence in what was being represented. We anticipated what cognitive mechanisms might be involved, and where they might be positioned in the flow of decision-making.

3.3.2 Diminished Quality of Life

The purpose of this step was to develop an instrument to measure long-term health, suitable to be used as a method to manage the risks in the industry.

Our approach was to identify the typical hazards in a manufacturing situation. Then, we determined the range of biological consequences for these, with a particular focus on the health issues. An initial hazards list was generated based on the literature [69] and health and safety legislation [32]. The specific area under examination for developing the hazards list was based on lathe work in a workshop. This list included items, such as 'Chemical Exposure'.

The literature concerning the potential biological consequences in the manufacturing industry was also examined from sources such as the International Classification of Disease in occupational health (ICD) [70]. A list of biological consequences was developed together with the level of harm. This analysis was related to the particular type of machine operation under examination. Examples of items on this list are: Skin Disease, Respiratory System Compromised, Blood Pressure Compromised, etc.

The next challenge was to link the hazards with the biological consequences. This is a many-to-many correspondence. This link was demonstrated using an ontology, using the Protégé software. This expressed the multiple biological consequences associated with the hazards.

Subsequently, we needed a measurement of harm. For this, we adopted the established WHODAS quality of life score [114]. We applied the WHODAS questionnaire to each of the biological consequences to determine the quality of life consequences of such a biological event.

Finally, we needed a framework to link these components into a coherent system that might be used to manage health in the workplace. We found that the conventional risk assessment methodology, with its strict demarcation between consequence and likelihood of the consequence, was unhelpful. Instead, we devised a new framework, which inverts the conventional process. It starts with the likelihood of an exposure incident arising (as estimated by engineering technologists and H&S officers), followed by evaluation of the likelihood of biological harm consequences in the situation (as evaluated by an occupational hygienist). The rest of the process is then mostly automatic, since it uses the previously established WHODAS scores. It results in a quantitative measure of the adverse effects of the work activities on the quality of life of the worker.

We call this the DQL metric. It is not the same as the conventional risk assessment method, and the results must be interpreted differently. See Section 5 for a discussion comparing the methods. We propose a set of thresholds and associated preventative mechanisms.

The DQL method is then applied to a case study.

3.3.3 Plant System Simulation for Engineering Workshops

The purpose of this step was to adapt plant systems simulation to optimise engineering training workshops.

The approach was for the first author to attend the course and become familiar with the workflow. This provided the contextual knowledge for development of a simulation model. The software used was Arena (version 15.1) [141]. Quantitative data were obtained from an expert, namely the workshop supervisor. These data comprised minimum, expected, and maximum times for each task.

The next challenge was to find a satisfactory solution. In this case, satisfaction is defined as a solution that minimises time waste (waiting time of students) and optimises machine utilisations. These are conflicting requirements, thus, a balance is needed. In this research, we define the optimising loops as *identify problems*, *develop solutions*, *test solutions*, *analyse the results,* and finally *adopt the positive solutions*.

Subsequently, optimising cases with different manufacturing attributes were designed. Attribute changes consisted of adding resources, removing resources, and changing the workflow. Optimising cases were then programmed in the simulation and analysed. Finally, the results of different optimised plans were compared, and a satisfactory solution was summarised. This methodology is shown in Figure 3.2.

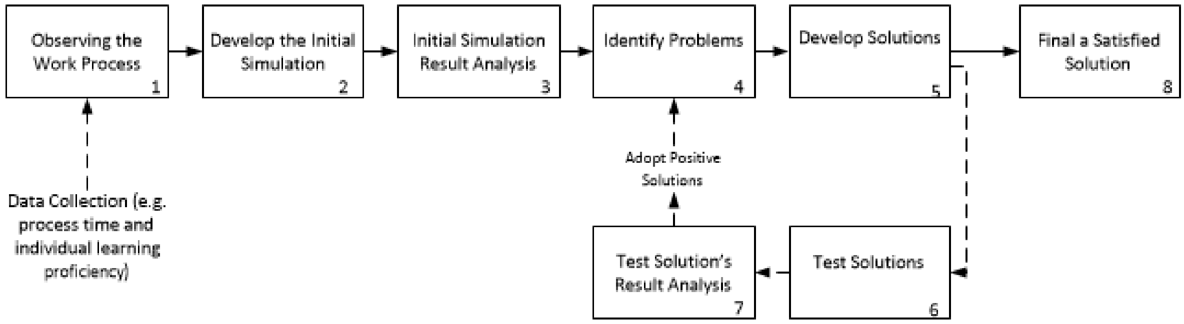

Figure 3.3: Methodology for plant system simulation

3.3.4 Integrating Occupational Health and Safety into Plant Simulation

An approach was sought to integrate H&S risk with plant simulation in the context of manufacturing industries. We refer to this integration as PSS.

The process adopted is illustrated in Figure 3.4. The starting concept is that the operations management, via the workflow and schedule, results in mobilisation of human and machine resources, which in turn results in exposure to various types of harm. The first step in developing a method of modelling this was to determine a suitable safety risk methodology. There are many existing safety risk methodologies; DQL was selected here. A further advantage of the DQL methodology is its inclusion of long-term health issues. The DQL methodology is based on frequency, likelihood, and consequence, and the simulation was adapted to accommodate these variables. The DQL also provides an integration with conventional risk assessment, thereby providing a mechanism to evaluate both the accident and long-term health risks. A method was then developed to integrate this into plant simulation (described below). Finally, the PSS method was applied to the specific case of a workshop for different types of machines, e.g. lathe, mill and CNC.

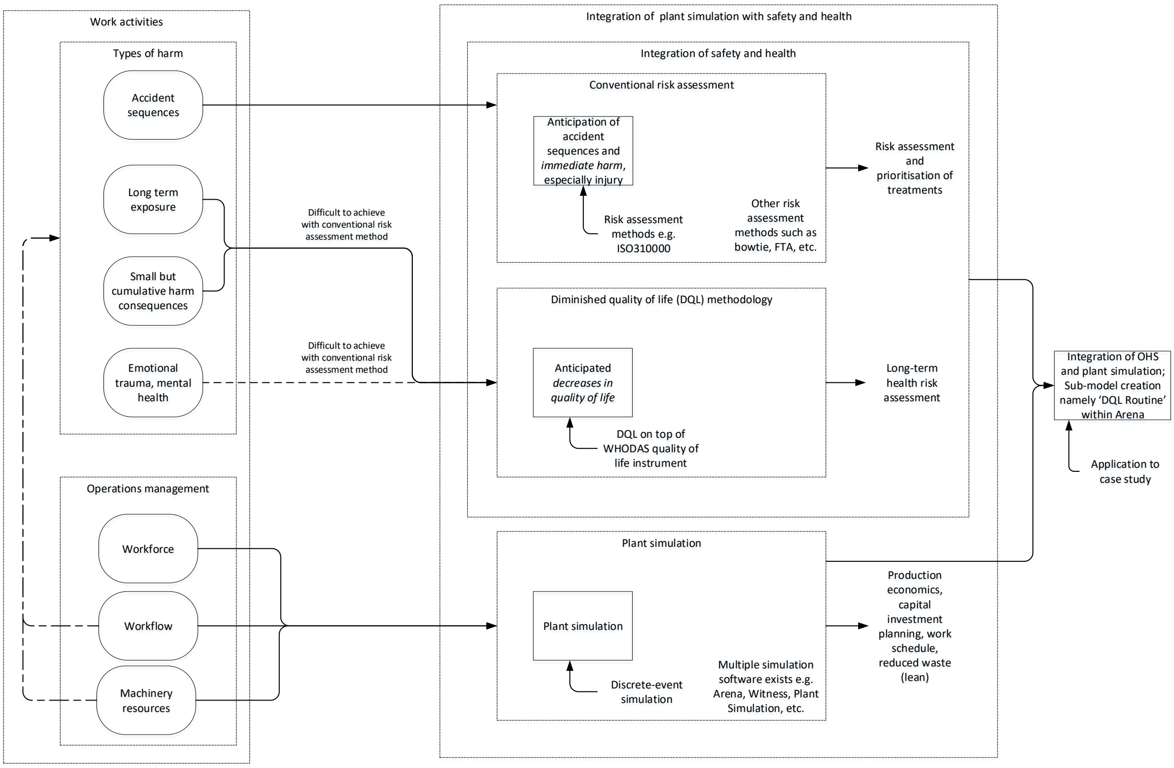

Figure 3.4: Summary of the PSS methodological approach, whereby conventional risk assessment was integrated with the health metric (diminished quality of life) and then with plant simulation.

An initial simulation was developed in Arena software (Version 15.0). This software incorporates a *decision model* which provides an efficient way to address the components in DQL, such as frequency and likelihood. DQL methodology was then combined with the workshop system in the simulation. We achieved this by creating, via programming, a *DQL Routine.* This was designed to calculate the safety risk for each part of the incorporated process. These routines are designed using several Arena models, such as *decision model*, *assign model* and *variable calculation model*. Instead of including all hazards, only a selection was included in the simulation, because DQL contains considerable OHS information, and we were seeking to develop a methodology. We selected some typical hazards, such as chemical exposure, cutting, crushing and squashing. The process whereby an integration of the DQL routine and plant simulation was achieved is shown in Figure 3.5. The integration achieved here was proof of concept, with the DQL routine being a manual programmed addition. Ideally, plant simulation software would enable this type of integration to be handled with less effort, and perhaps this is a potential future development area for software development.

Following integration of DQL into the simulation programme, we built different simulation scenarios to investigate the effects of the different activities on the plant model.

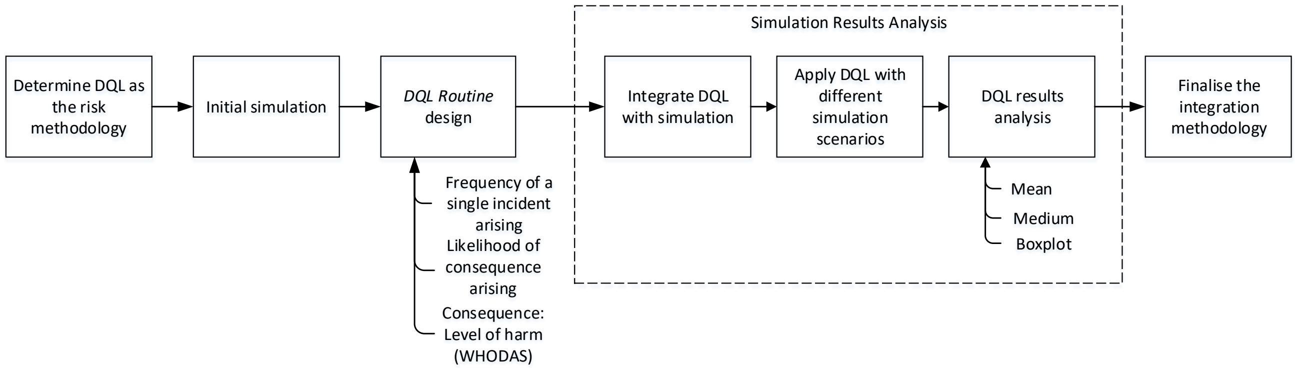

Figure 3.5: Integration of DQL routine and Plant simulation

3.3.5 A Methodology Simulating Production Economics and Safety Risk for SMEs Growth

A safety induction was firstly introduced by the SME and this was followed by onsite observations. The observation included collecting information related to the production economics (for example, plant layout, workflow, potential improvement plan, and time distribution), which was then used for developing the simulation model. The time distribution of each process was provided by the SME.

H&S information was then collected using DQL methodology. Estimations of the frequency and likelihood of incidents were generated in consultation with the H&S representative of the SME. Biological consequences were determined by DQL methodology using WHODAS 12-items [2].

An initial simulation for the status quo was then developed using Arena software (Version 16.0), which is based on discrete-event simulation (DES). A DQL routine was employed to combine the plant simulation with the associated H&S risk. The DQL routine consisted of three parameters: frequency of the incident, likelihood of the consequence, and level of harm. These parameters were collected using DQL. The routine was created in the Arena simulation using *assign model*, *decision model*, *routine* and *station*. The simulation provided the final OHS risk result. An improvement plan of the simulation was then generated after discussion with the plant manager, production engineers and H&S representative.

The DQL risk and production economics related results, such as process time, were then compared to the status quo and improvement plan. Boxplot analysis was used to manage DQL results for each biological consequences and scenario. Capacity flexibility was then determined based on the improvement plan.

3.3.6 Validation

It is not possible to quantitatively validate the methods in any of the risk assessment methods, except where longitudinal studies are performed. In the case of chronic harm, numerical data on exposure vs biological consequence are lacking in the literature. Hence, it is necessary to provide a qualitative validation. This is not necessarily problematic, since the legal obligation is to do what is *reasonably practicable* to reduce adverse H&S consequences, and conventional methods achieve this adequately using qualitative methods. In the present work, the integration of DQL and plant simulation was validated with two case studies, one in a training workshop and the other in industry. The validation mechanism was verbal discussion and confirmation from production managers about the veracity of the findings. A further, more conceptual, validation was provided by integrating the method with the conventional risk assessment method (which is also a qualitative method).

Chapter 4: Conceptual Health and Safety Model Building – RASH Model

This chapter contributes to the following publication:

Ji, Z., Pons, D., & Pearse, J. (2018). Why Do Workers Take Safety Risks?—A Conceptual Model for the Motivation Underpinning Perverse Agency. Safety, 4(2), 24. doi: https://doi.org/10.3390/safety4020024

4.1 Chapter Introduction

Exposure to chronic harm is difficult to manage and prevent in industry. There is a need to better understand the state of mind when workers disregard safety processes and expose themselves to this type of risk. This paper develops a theoretical model of the reason why workers voluntarily expose themselves to occupational health and safety (OHS) hazards. This Risk, Agency, and Safety & Health (RASH) model proposes that people willingly expose themselves to chronic injuries via a series of risk-taking processes. This causal chain starts with personal motivation and over-alignment with organisational purpose (including impression management). Ideally, that motivation would be moderated by an ability to predict future harm consequences from the task at hand, but that mechanism is weak because it is difficult to predict cause and effect, the consequences are too far in the future, and the opportunities for vicarious learning are few. The motivation then causes misdirected creativity, hence the development of personally novel ways of solving the problem, albeit with greater risk of harm. Perverse agency then sustains actions that exposure the person to harm. Original contributions are the provision of a detailed explanation for risk-taking, and the integration of multiple well-established psychological constructs.

4.2 Approach

4.2.1 Purpose

The purpose of this research was to develop a model to explain the causality whereby people take short cuts in personal occupational health and safety. We wished to understand the human factors and the flow of conscious and subconscious decision making that affect hazards exposure.

4.2.2 Methodology

A qualitative methodology was applied to develop the model. We started by examining the literature for relevant constructs in the occupational health and safety literature. We then developed an initial model that sought to describe how workers' motivation affects their actions. This was presented to the annual general meeting of the New Zealand Society of Safety Engineering ('Occupational health in an industrial context—Overview of UC research project', 25 January 2017, IPENZ, 50 Customhouse Quay, Wellington, New Zealand) and discussed by a group of eight professional engineers with expertise in safety engineering. They provided a critique of the model, identifying areas that were well represented and also those that were underrepresented. From this early work arose the idea of perverse agency (described below). These discussions were used by the authors to further refine the model.

Subsequently, there was an individual discussion with an engineer from a construction firm, and this resulted in further refinements. We then examined the Pike River Mine disaster [62], from which we extracted additional principles of how incentivisation could affect workers motivation towards unsafe acts. From this arose an element in the model relating to over-aligned with organisational purpose.

The next stage in the development of the model was the adoption of several constructs from psychology and organizational behavior, e.g., personality, dark triad, and motivation theory. Doing this grounds the model in the wider literature. The psychological constructs themselves are not critically evaluated here; rather, it is the integration of them into a wider model that is new. Consequently, the constructs are defined at first usage in the results, rather than being described in the literature review above.

Moving to completion, we then developed the model to explain why workers might appear to willingly forgo their own safety to complete a task. Throughout the development, we applied a methodology. Specifically, we represented the ideas as a flowchart with proposed causal mechanisms, and we continuously revised it to ensure coherence in what was being represented. We anticipated what cognitive mechanisms might be involved, and where they might be positioned in the flow of decision-making.

4.3 Results: the RASH Model

4.3.1 Overview Model

We propose that workers approach H&S decisions in a sequential manner, starting with an evaluation of the task at hand. They then apply their personal agency to execute the task, and an H&S outcome emerges. This simple linear model is shown in Figure 4.1.

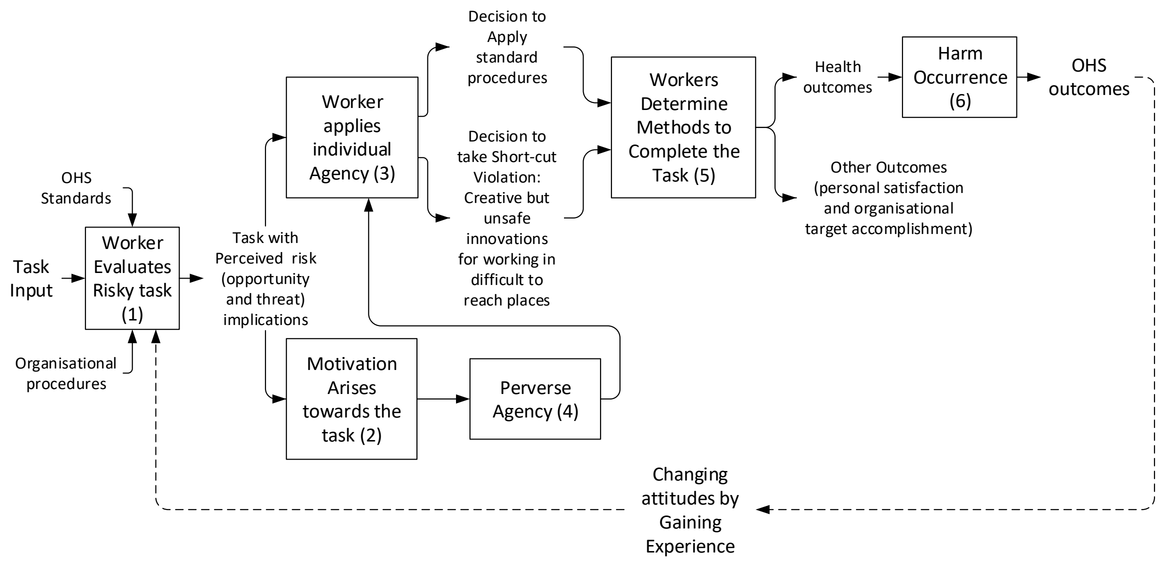

Figure 4.1 The RASH Model.

However, the process is complicated in several ways. Firstly, there are situational variables in the form of OHS standards and standard operating procedure that will affect the worker's decision. Secondly, there are management and organisational culture variables that will shape the response. Thirdly, there is learning that occurs: people gain experience and this influences their future decision making. The result of this process is that agency is applied in positive or negative ways. Later, we propose that the antecedents for perverse agency primarily occur early in the process, at the stage, when the worker is evaluating the risky task.

We term this the RASH model as it encompasses these various effects. Additionally, it proposes mechanisms whereby workers make imprudent decisions, hence perverse agency.

The following sections elaborate on this concept by progressively detailing each process.

4.3.2 Process 1: Worker Evaluates Risky Task

We propose that workers take a pragmatic approach to their initial evaluation of risks within the task at hand. Specifically, we propose the existence of two key factors in the decision-making. The first dimension is the perceived task novelty, wherein the task is evaluated for the degree to which it is well-defined or novel. The second is the perceived residual risk, which is the worker's evaluation of the extent to which existing treatments are effective at preventing the risk. We propose that these factors interact in the following manner.

A: Low Task Novelty—Low Residual Risk

For a safety system that is within control, i.e., functioning effectively, the task is routine (has been standardised) and the existing treatments (e.g., procedures, PPE) are effective. Therefore, the worker is not exposed to unreasonable risk.

B: Low Task Novelty—High Residual Risk

In situations where the safety system has inadequately assessed the risks, the treatment might be ineffective, even for routine tasks. This arises because the organisation or the worker has not validated that the treatment is indeed effective. Thus, a larger residual risk is presented to the worker than expected. The worker undertakes the task naively and this results in inadvertent exposure to known hazards. It is worth noting that, in terms of legislation, it is the duty of the organisation and its executives, not primarily the worker, to validate that the treatments are effective.

C: High Task Novelty—High Residual Risk

Another situation is where the tasks are perceived to be novel, and the worker correctly identifies that the existing treatment does not fully control the threat. Thus, there is a known and significant residual risk. The work requires additional safety precautions and treatments to deal with the new risk. At this point, the worker has a choice: to refrain from doing the task, or to proceed with personal acceptance of the risk. The latter choice results in conscious exposure to the hazards.

D: High Task Novelty-Low Residual Risk

The fourth situation is that the worker correctly perceives the task to be novel, but it fails to recognise the new risks therein. We anticipate that this situation arises from a lack of situational awareness, ineffective hazard assessment, poor training, or failure to anticipate cause and effect. Thus, the worker fails to perceive the new hazards in the situation, and persists with work procedures that are inefficient proof against those hazards. This results in ignorant exposure to new hazards. The ideal organisational practice is that the resulting near-accidents will be reported, and will result in the eventual re-assessment of the hazards in the situation and better future protection.

This proposed causality is summarized in Figure 4.2. The diagram represents the branches of decision-making made by the worker in the various situations. It also shows the proposed causal mechanisms (arrows entering under the actions) and the constraints on those actions (arrows entering above). The numbers in circles represent call-outs to locations in other diagrams.

We also propose a further simplified model, which is one that ignores the causality and simply represents the outcomes as a function of the inputs. For this model, we assume that the two input dimensions are orthogonal, resulting in a 2×2 matrix of outputs, see Figure 4.3.

It is evident that significant numbers of people do make the choice for conscious exposure to the hazards (output C). In the next part of the model, we speculate on the motivations for this behavior, and we introduce the term 'perverse agency' to describe it.

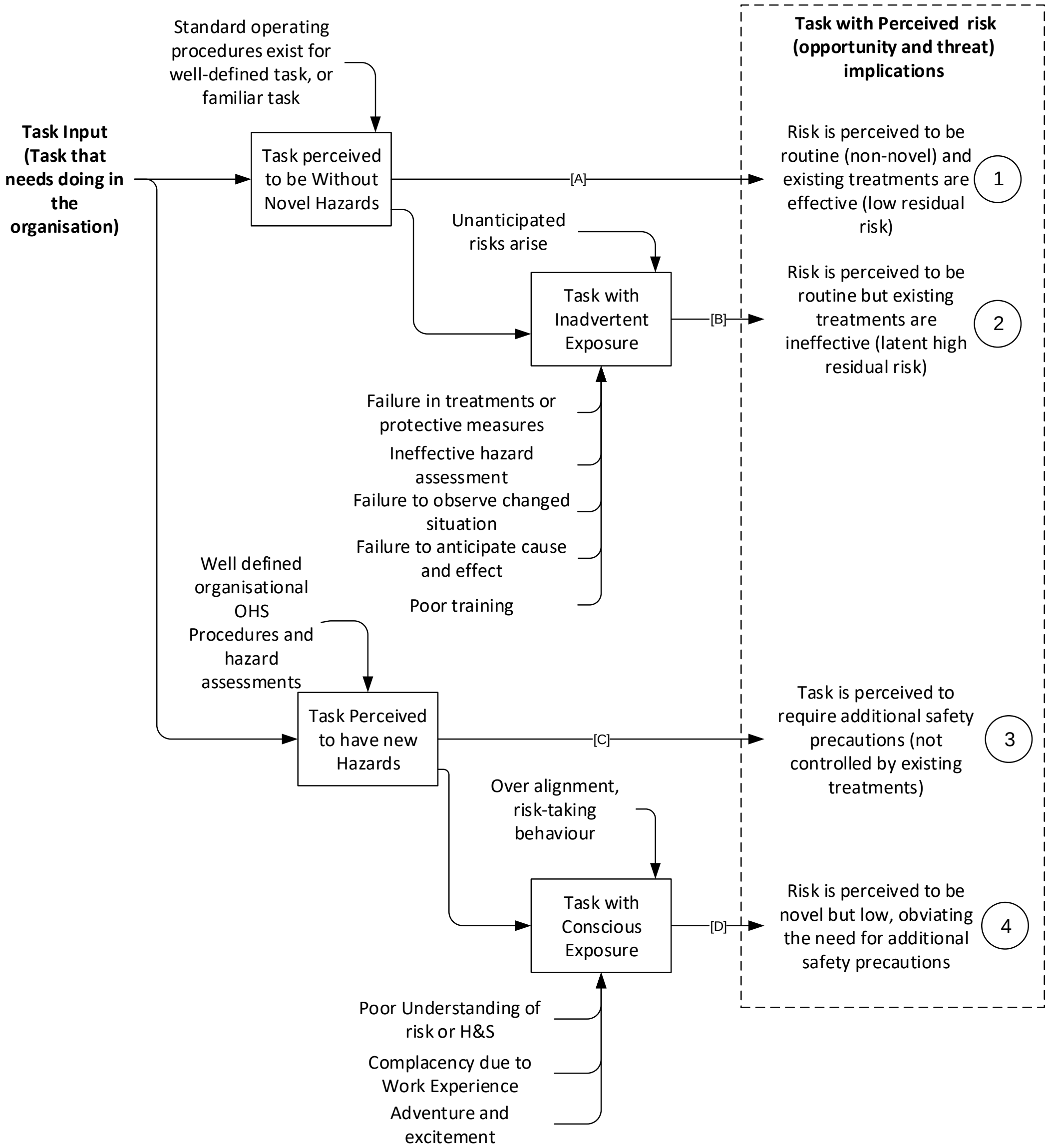

Figure 4.2. The Worker Evaluates Risky Task Model.

	Existing Effective Treatment - Low Risk	Ineffective Treatment - High Residual Risk
Novel Task	D Risk is perceived to be novel but low, obviating the need for additional safety precautions	C Task is perceived to require additional safety precautions (not controlled by existing treatments)
Routine Task	A Risk is perceived to be routine (non-novel) and existing treatments are effective (low residual risk)	B Risk is perceived to be routine but existing treatments are ineffective (latent high residual risk)

Figure 4.3. 2 × 2 Risk Task Matrix.

4.3.3 Process 2: Motivation Arises towards the Task

We propose that motivation arises before workers make any H&S short cuts, see Figure 4.4. Specifically, we propose as a first approximation that intrinsic and extrinsic motivation operate somewhat independently of each other. The intrinsic factors are internal personal choices, whereas the extrinsic factors arise in the organisational environment that surrounds the worker. However, we also propose that the separation is not absolute, and we identify pathways whereby these factors mutually affect each other.

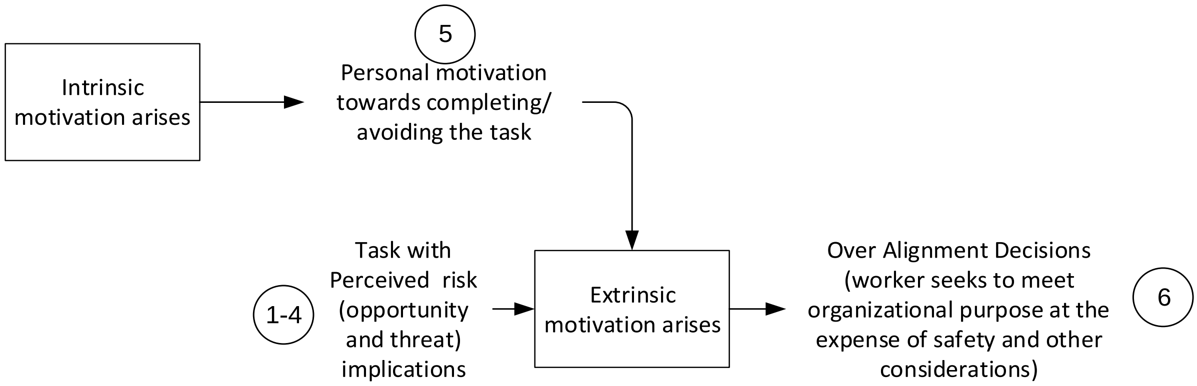

Figure 4.4. Motivation Arises towards the task.

4.3.4 Intrinsic Motivation

Intrinsic motivation (IM) refers to internal or personal motivations that can affect one's behavior [56]. In this model, IM affects work attitude and personal valance (attitudes towards reward and punishment). We propose that there are five main characteristics within IM. These are: A: Personality (especially Conscientiousness), B: Personal Worldview, C: Self-efficacy, and D: Dark Triad. We propose that there are four main routes that can affect intrinsic motivation and result in personal choice in safety behaviors, as per the explanation below and the representation in Figure 4.5.

A: Personality

Personality refers to enduring individual styles of behavior. This affects how people respond or behave in situations, and it can effect performance [200]. The five factor model (FFM), also known as the Big 5, is the dominant description of personality [201]. The factors are Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism (OCEAN). Of these factors, we propose that conscientious is the key characteristic in the safety situation, and we suggest it contributes to a positive work ethic. Conscientiousness refers to a cluster of attributes that include carefulness, hard-working, vigilance, reliability, dependability. Generally, conscientious people are self-disciplined, and prefer planning rather than spontaneous behavior. We also propose that conscientious people are more likely to accept a task with unknown risk, because their internal sense of responsibility can affect one's agency and then can be over-aligned with the organisational purpose, see following Section 4.7, Process 4. This is consistent with the literature, where conscientiousness is specifically associated with health and safety attitudes [202] and workplace performance [80, 203]. The five-factor model of personality was deliberately designed to avoid pejorative meanings. Consequently, the extremes of all its scales are intended to be non-condemnatory. The behaviours it describes are neither good nor bad—instead, they are merely styles of interaction. However, the reality is that people do behave in selfish ways, and this needs to be included.

B: Personal Worldview

Personal worldview is another attribute that effects the worker's motivation towards safety. A worldview is the totality of a person's perspective on the world and the values that they seek to embody in their own life. Belief systems are the mental constructs that individuals and groups create to make sense of themselves and their spiritual place in the world. They provide an existential postulate. They are based on faith–not necessarily religious. The world view is coherent to the person who holds it—its makes sense to them. It is also strongly held, in that people will not easily change their view. Individuals within a culture share elements of the same world view.

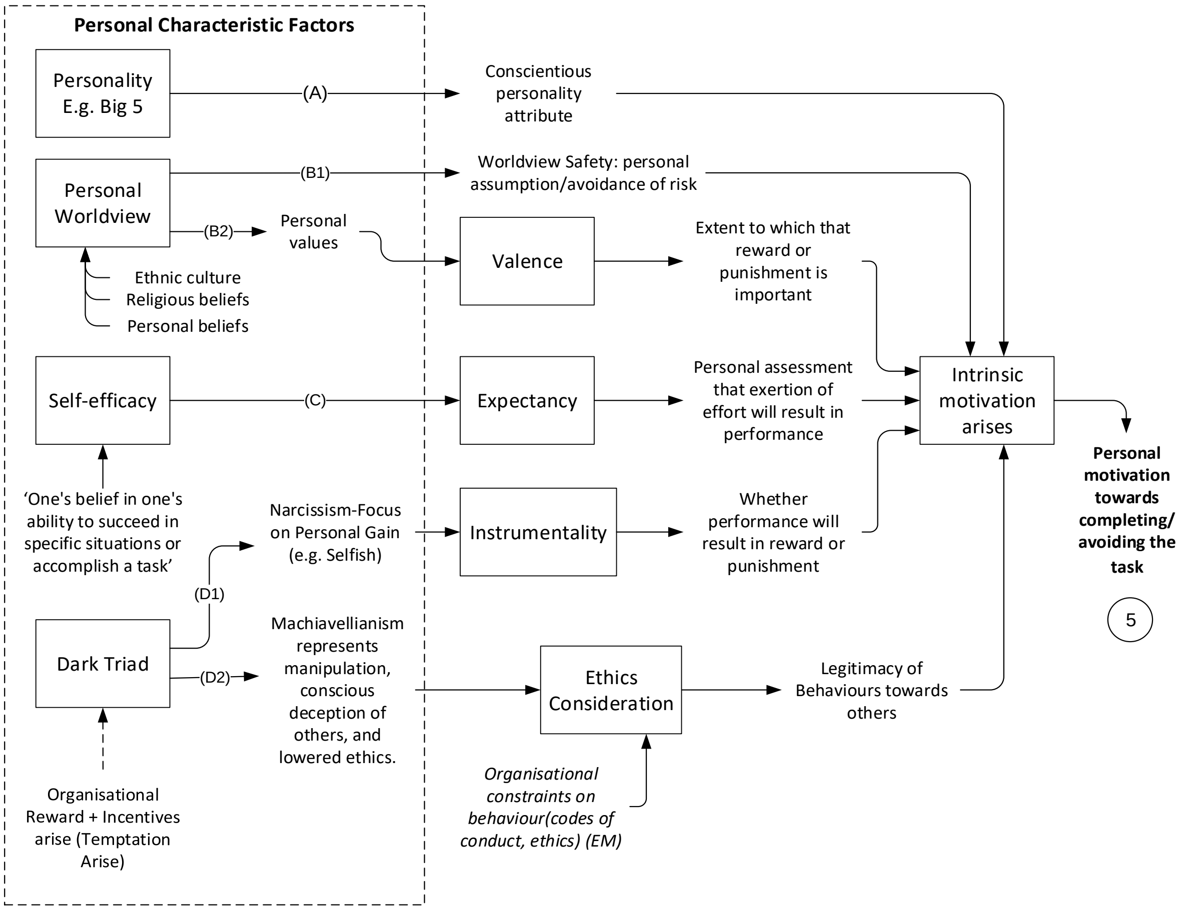

Figure 4.5. Intrinsic Motivation Model.

No amount of information will change a worldview. They are deep seated beliefs that are linked to personal identity. Conflict can arise between people with different world views. The conflict is about the values. Personal value system is structured by one's world view; and, it tells a person what is good, important, and desirable. Consequently, in the safety situation, it provides a mechanism that creates an intrinsic perception of right vs. wrong regarding safety, see Figure 4.5 and route B1 therein.

Furthermore, we propose a second route whereby personal worldview affects attitudes towards safety. This is via the value systems of the worldview affecting the valence; therefore, the extent to which a particular outcome has value to the individual, see Figure 4.5 and route B2 therein.

It is expected that these personal values will be affected by upbringing, environment, ethnicity, culture, etc. This is consistent with others in the literature who have proposed that personal value systems play an important factor in personal behavior for health and safety [204]. There are many situations in societies where these personal worldviews cause people to accept significantly higher safety risks than usual, a common example being war. The effect is also evident in industry, and results in workers making personal sacrifices to improve the organisational outcomes, examples being a Chinese oil drilling worker called Wang Jinxi who achieved hero status by jumping into the mud pool of an oil drilling well to stir the mud with his body, and hence, keep the well operating. This example of positive work attitude continues to affect and reinforce the Chinese value system and worldview about work ethic. Consequently, we propose that worldview affects the personal assumption or the avoidance of risk.

C: Self-Efficacy

Self-efficacy is the confidence in one's own ability to achieve intended results [205]. As such, it refers to a personal approach towards problem-solving and persistence at a difficult problem, rather than merely self-confidence (which may be potentially misplaced). It has a positive effect on expectancy, general decision making [206], and work engagement [207]. The attribute is also associated with internal locus of control. Self-efficacy is believed to be developed by personal experiences and the external social factors that accompany them (such as encouragement and social learning) [204]. The role of self-efficacy on safety has been noted in the literature, and has, for example, been found to correlate with safety behaviours of pilots [208] and medical doctors [209]. There is also evidence that the locus of control is associated with safety behaviours for truck drivers [210]. It has been shown self-efficacy regarding safety in a steel plant is associated with several organisational factors relating to team communication and supervision [211]. It is also possible that workers take risks as part of impression management—as part of a need to present themselves positively to others, and hence undertake risk-taking activities. We propose that self-efficacy affects motivation directly via the expectancy route.

D: Dark Triad

In the present model, the selfish attributes are included using the Dark Triad of personality. The attributes are: Machiavellianism, Narcissism, and Psychopathy [212]. These represent different aspects of malevolent selfishness, and they are all associated with manipulative actions to further their own advantage at the expense of others. Machiavellianism represents manipulation, conscious deception of others, and lowered ethics. Narcissism is characterized by egotism and "excessive love for one's self, feelings of superiority, attention seeking, and exploitativeness in relationships with others" [213]. Psychopathy refers to callous behavior towards others, and can include impulsivity and low remorse [213]. The Dark Triad has previously been applied primarily in the psychology literature, and it is used to explain situations, such as bullying [214] and aggression [215]. Also, the attribute of sensation seeking, which might be considered as another aspect of narcissism, has been associated with risk-taking in skateboarding [216]. The general concept of the Dark Triad has not previously been applied to safety considerations. We proposed that personal dark triad can have an effect on instrumentality. This is because people may balance the rewards and punishment before making an action. Specifically, we propose that the Narcissism factor increases the Instrumentality of the motivation (pathway D1 in Figure 4.5). Also, that the Machiavellianism factor affects ethical considerations, as elaborated below (see pathway D2, Figure 4.5).

E: Ethical Considerations

Ethical considerations are the moral constraints that organisations set on the behavior of their members. Ethics may exist independently on any personal worldview or religious belief. Ethics internally limits a person to avoid actions that would cause harm to others at work. It provides a judgement mechanism that constrains decision-making in order to preserve the well-being of people. We propose that it primarily acts in the interests of others, and it has a weaker effect regarding self. Consequently, it acts contrary to the selfish decision-making priorities of the dark triad. The intersection of ethics with H&S is a developing area within the literature [217]. Codes of ethics for the engineering profession often include a duty of care for the H&S of others. Likewise for other professions. Organisations, especially government departments, may have codes of conduct for their staff, although this is not universal. However, workers are not usually covered by codes of ethics. Consequently, workers may not be subject to an explicit ethical code, though they do still have their own personal moral considerations. These may be based on their culture, religion, and worldviews. In the present model, we propose that ethical considerations include the self-assessment of the legitimacy of behaviours towards others, and hence moderate the Machiavellianism.

4.3.5 Extrinsic Motivation

Extrinsic Motivation, defined as the motivation that effected by external factors that arise outside of the individual. Extrinsic Motivation is virtually opposite to Intrinsic Motivation. In this context extrinsic motivation (EM) refers to the external factors that are caused by the work environment. These arise outside of the individual, though they interact with and recruit aspects of intrinsic motivation. We propose the following model of how organisations affect the motivation of workers, see text below and Figure 4.6.

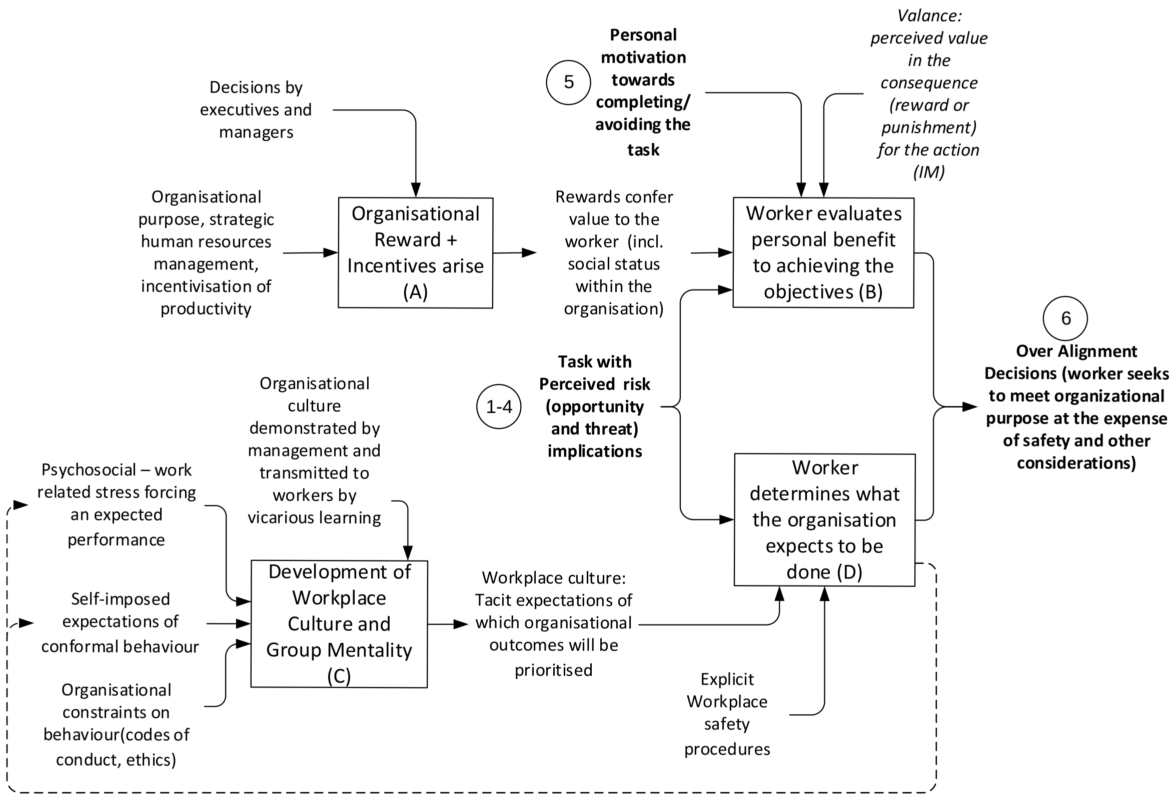

Figure 4.6 Extrinsic Motivation Model.

A: Organisational Reward and Incentives

Organisations exist to fulfil a purpose, and executives and managers make decisions that advance that purpose. The mechanisms used are strategic human resources management, and incentivisation of productivity. These can be affected by external rewards, such as remuneration, extra vacation, and promotion. These rewards confer value to the worker, including social status within the organisation.

B: Worker Evaluates Personal Benefit to Achieving the Objectives

Given a Task with its perceived risk (opportunity and threat) implications, the worker considers the personal rewards that the organisation is offering for completing the task, and evaluates the valance thereof. Therefore, the intrinsic and extrinsic motivational factors intersect at this stage. This, we propose, is the first factor that determines the extent to which the work aligns with the organisational purpose. Over alignment occurs when the worker seeks to meet organisational purpose at the expense of safety and other considerations.

C: Development of Workplace Culture and Group Mentality

Workplace culture and group mentality affects peoples' behavior generally [218, 219], and it is known to affect their attitudes towards safety in particular [220, 221]. This may occur via peer group pressure [202]. Recent research has identified that the creation of a safety-oriented culture requires training [222], systematic organizational processes [223], commitment from management [224], responsiveness to new conditions [225], and national efforts [226]. However, safety culture is difficult to define [227], difficult to measure [228, 229], and the relationships between safety climate and safety behavior are not straight forward [230, 231].

We propose that group mentality and other developments of workplace culture may have effects on what the organisation implicitly expects to be done, especially its organisational targets. A positive safety culture is proposed to be one that generates belief in workers that accidents are preventable if personal agency is applied. This is related to the concept of causal attribution [232], which in turn, is related to error disclosure [233].

We propose that safety culture is created and demonstrated by management, and is transmitted to workers by vicarious learning (observing how the organization actually behaved in the past). A psychosocial factor is anticipated whereby work related stress forces the individual into an expected performance. Self-imposed expectations of conformal behavior are proposed to contribute to a collective culture, even if that culture is not explicitly articulated. There can also be explicit organisational constraints on behavior (e.g., codes of conduct, ethics). Consequently, the workplace culture provides tacit expectations of which organisational outcomes will be prioritised.

D: Worker Determines What the Organisation Expects to be Done

Workers are presented with a task for which they have a perceived risk. We propose that they determine their personal course of action by balancing tow considerations: the explicit workplace safety procedures (e.g., the need to wear PPE), and the tacit expectations organisational priorities via the organisational culture. In a negative situation this may involve the worker determining that the organisation values productivity more than say safety, even if it has explicit safety systems. In a positive situation, the worker would value safety as an equal priority to productivity, and this might mean doing the task slower (hence, lower productivity) to preserve the safety priority. It is not only the presence of safety protocols and provision of PPE that is important—there also needs to be a culture that prioritises safety equally [234] with other organizational objectives [235], rather than relegating safety to a secondary consideration. Organisations need to consciously work on developing positive safety culture [236] (see also above). Safety nudges may also be useful [237], although this is a developing field.

E: Alignment Decisions

Finally, we propose that the worker make a cognitive calculation that combines the perceived personal benefits (B) and the expectations of what action is expected from the organization (D). This calculation may not even be conscious or explicit. The adverse outcome that potentially arises is one of over alignment, where the worker seeks to meet organizational purpose at the expense of safety and other considerations.

4.3.6 Process 3: Workers Determine Approach

We propose that after evaluating the risk in a task (process 1), workers determine their approach to the task. This is primarily a decision process, hence one of personal judgement. The decision may be made consciously or subconsciously. Two main outcomes are anticipated: A decision to apply standard procedures, or to take short cuts. The latter are violations: Creative but unsafe innovations for performing the work. The proposed inner workings of this decision are shown in Figure 4.7 and are described below.

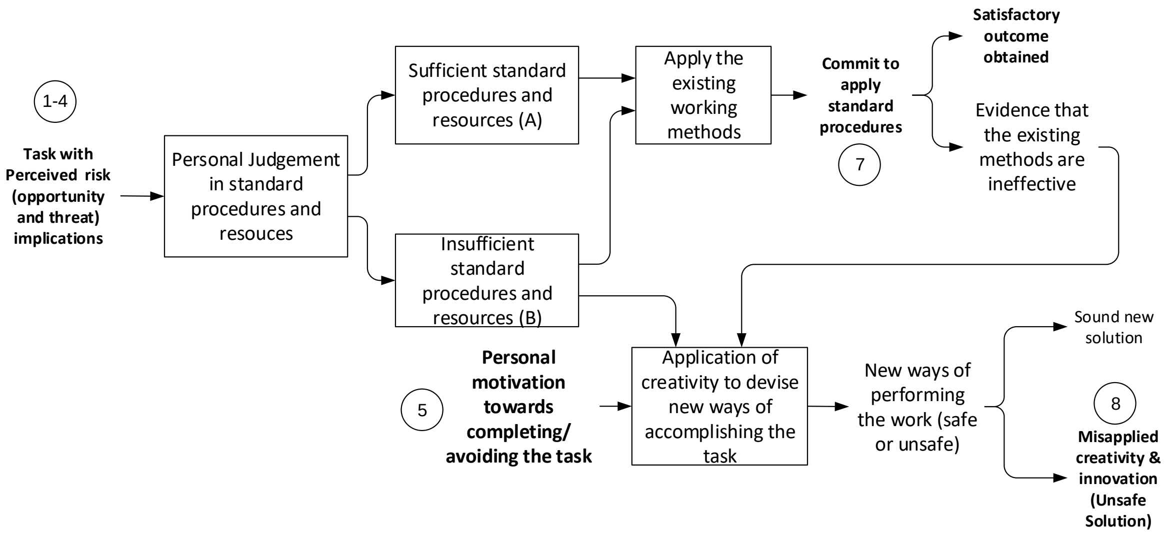

Figure 4.7 Workers Determine Approach.

Personal Judgement

First, we propose that personal judgement is a key factor. In this context, we propose that judgement refers to the ability to identify the multiple alternative solution paths that might exist, the ability to select between these paths based on the benefits and detriments of each in the situation, and the ability to explain and justify their choice. Part of judgement is therefore the ability to adapt to different situations, and to recognize that certain solutions have the potential for adverse outcomes in specific situations. People lack judgement if they fixate on one solution path, irrespective of its appropriateness in the situation.

Resource Determination

As a consequence of the application of judgment, the worker makes a decision and this commits them to a subsequent process of evaluating whether their course of action is sufficiently provided with procedures and resources.

A: Sufficient standard procedures and resources

In this situation, we propose that the current standard procedures and resource can be trusted and the worker believes that they are functioning effectively. Therefore, the worker commits to apply these existed working methods to complete the task.

B: Insufficient standard procedures and resources

In this situation the worker deems there are insufficient standard procedures and resources. Then, the worker may apply those procedures anyway and hope for a favourable outcome. Alternatively, the worker may apply creativity to devise new ways of accomplishing the task. We propose that this occurs when there is personal motivation towards completing/avoiding the task, or the procedures are deemed to be insufficient, or they have previously been shown to be ineffective. Importantly, the outcome may be safe or unsafe.

4.3.7 Process 4: Perverse Agency

Bandura's theory of self-efficacy describes a person's belief in their ability to achieve goals [238, 239]. Agency, per Bandura's concept [240, 241], is that people commit their effort in a deliberate way to achieve goals that they have anticipated and have confidence in their ability to succeed. This has developed into a broader construct, which is referred to as sense of agency, personal agency, or human agency. It may also be related to Vroom's Expectancy theory [52]. For example, expectancy has been theorized to have a direct effect on self-efficacy judgments [242].

Personal agency is a positive feature of human tenacity [243], but we propose that it has the potential to be recruited to perverse outcomes, i.e., the sense of commitment may be directed towards doing an action that is unwise. This contrasts with the literature, wherein agency is seen as a positive attribute. We do not deny the positive aspects of agency, but propose that it can be directed negatively towards the completion of acts that should not have been done, hence perverse agency. We define it thus:

Perverse agency is application of poor judgement whereby the protagonist persists (by showing decisiveness, action, and commitment) with an unwise course of action and willing assumption (personal acceptance) of risk that others would consider unreasonable, to achieve what they feel is a good objective.

This idea is potentially applicable to many different areas of human decision-making. In the safety context, we propose that process involves the following contributory activities, as described below and represented in Figure 4.8.

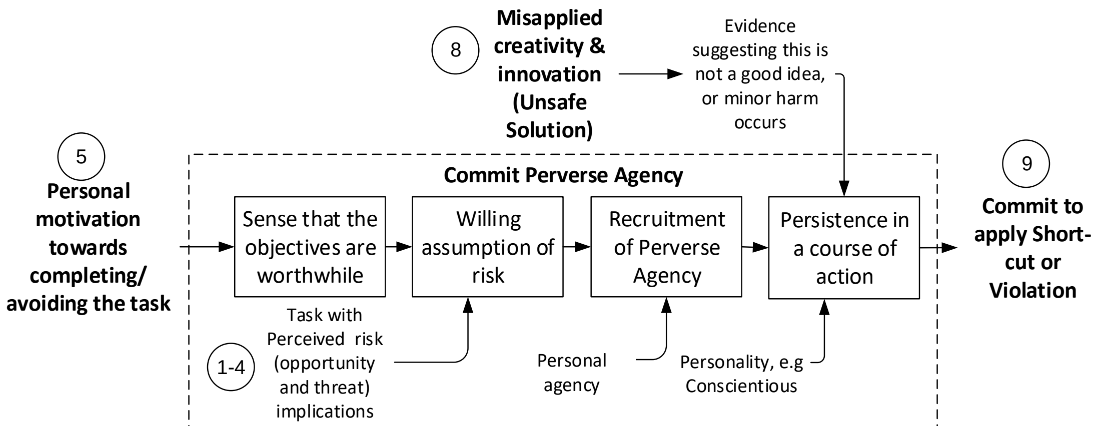

Figure 4.8 Perverse Agency and Over Alignment Model.

Firstly, a worker has a personal motivation towards completing (or avoiding) a task (see Intrinsic motivation above). Included here is the sense that the objectives are worthwhile to achieve. This is followed by a willing assumption of risk, which in turn, is informed by the prior judgement of the risk inherent in the task (see Process 1 above). Unsafe actions are therefore proposed to be preceded by errors in judgement, wherein either the objectives are over-valued, or the threats are under-appreciated.

The next stage is the commitment of personal agency to attempt to achieve the outcomes decided in the previous stage. Personality is proposed to be involved in perverse agency, via the conscientious personality characteristic [201]. Conscientious workers are reliable, and they desire to complete a task well. They also wish to persistence in a course of action until they finish the job. They may be more loyalty to their employers or organisation. These characteristics make conscientious workers not afraid to accept challenges at work. In the case of hazards, they may prioritise work accomplishment rather than safety, or even consciously take actions that are personally hazardous for themselves for the sake of completing the work.

This recruits a continuation of agency in that the worker persists with the course of action despite disconfirmatory evidence, i.e., evidence suggesting this is not a good idea, or the occurrence of minor personal harm. There may also be an element of misapplied creativity and innovation, in which the worker finds an unsafe but expedient solution (see Process 3). Furthermore, we propose that workers may be inaccurate judging their ability, i.e., their self-efficacy may be unreasonably inflated. This may be because of their excessive expectancy in the outcomes [244].

The end result is that the worker commits to applying a short cut or violation. This is related to, but not identical to assumption of risk (risk-taking). With the assumption of risk, the worker accepts a known risk [245], but in the more generalized situation of perverse agency the worker does not necessarily consciously think about the risk, neither the long term consequence nor the likelihood thereof. The personal efficacy suppresses such considerations.

4.3.8 Process 5: Worker Executes the Task

The “Worker executes the task process” model (shown in Figure 4.9) describes what the workers do after they commit to do a risky task.

The first situation is that workers refuse to do the task. This is because the detriments are unacceptable relative to OHS standards and regulations. However, to complete the work, managers and supervisors may then try to find some new methods in order to reduce the risk. This may result in effectively returning to Process 1, i.e., the start of the model.

Another situation is that workers accept to do the task and they are willing to be exposed to the residual hazards. In this situation, workers may use safe procedures or engage in short cuts, depending on their decisions earlier in the process (see Process 3).

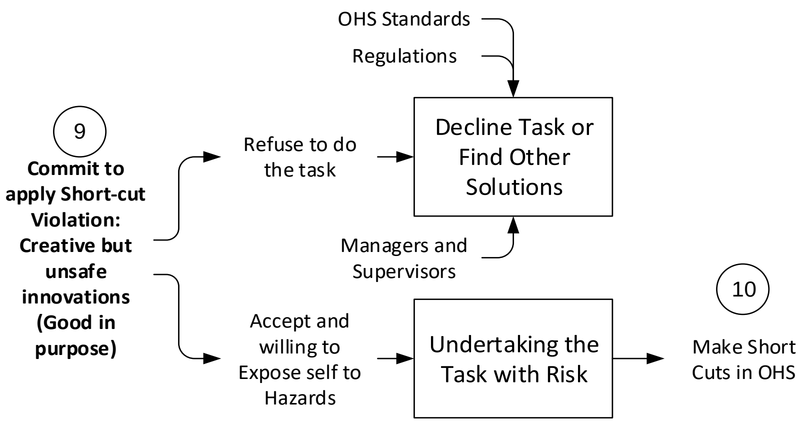

Figure 4.9 Worker executes the Task Process.

4.3.9 Process 6: OHS Outcome

The final OHS outcome model illustrates the process from harm occurrence to recovery, see Figure 4.10. Here, we are particularly interested in representing the chronic harm condition, and its relationship to the assumption of risk, perverse agency, and misapplied creativity of the previous stages. Two pathways are used to address the different situations when harm occurs to the human body.

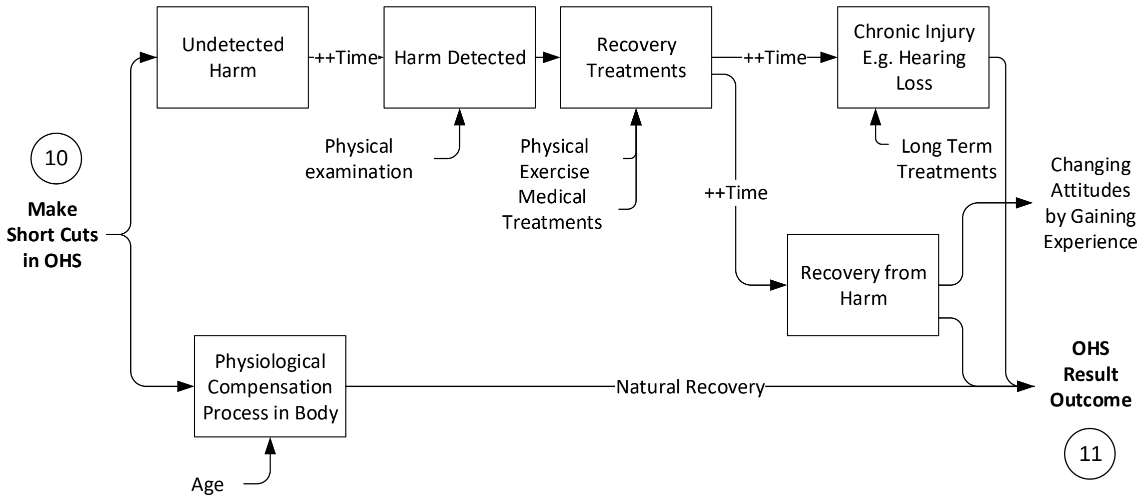

Figure 4.10 Occupational Health and Safety (OHS) Outcome Process Model.

The first situation is that natural recovery takes place, and the person recovers full functionality. The worker may not even feel the effects of the injury if the recovery process is faster than the damage inducing mechanisms. The ability for the human body to heal is dependent on age; thus, a degree of risk-taking may be more tolerable for younger than older people.

The second, and more general, situation is that the harm accumulates, often without initial detection. The harm may occur by cumulative exposure (e.g., to noise or chemical compounds), or have a period of latency before symptoms develop (e.g., carcinoma). Subsequently, some time later, people detect their health problem, thus chronic harm/injuries arise. Frustratingly, for prevention efforts, the long latency often means that (a) enduring harm is already done and it is too late to apply prevention or to desist from performing the tasks, and (b) it is not always possible to explicitly identify the original injury mechanism, offending task, or place of work. The latter has the further consequence that the industry does not get timely feedback that certain tasks are unreasonably harmful, i.e., the continuous improvement loop is not closed, and furthermore, the person may not qualify for workers' compensation or free healthcare.

Examples of these chronic injuries include musculoskeletal disease, loss of hearing, and persistent pain. People with chronic injuries may or may not have access to medical treatment, depending on their personal financial situation and the extent of public medical coverage. Chronic injuries tend to reduce peoples' ability to work, and hence reduce income. With time, some people recover functionality, some only partially, and others not at all. At the same time, people are getting older, and natural regenerative healing mechanisms are slower, and other age-related health issues arise to complicate the situation.

Chronic injuries can be seriously debilitating in developing countries, the poor, and the elderly. Furthermore, chronic injury can contribute to anxiety and psychological poor health [246]. People who suffer a chronic injury may have a significant decrease in their quality of life (QOL). There are instruments to measure this loss [114].

Those who do recover and are young enough to still be in employment may find themselves exposed to the same health and safety hazards again. Ideally, their experience of poor health may cause them to be more attentive to their work practices. This is illustrated by the feedback loop in Figure 4.5. We expect that many workers, especially those who are young and have not experienced medical incidents of any kind, are unable to predict the health consequences of their perverse agency. They do not feel any immediate harm from performing the task, and they are unable to anticipate how it may affect them when they are older. They may even be emboldened to perform risky tasks for the sake of gaining social esteem within the work group. They do not necessarily learn vicariously from seeing how chronic injuries adversely affect the quality of life of older people. Sometimes, those older people are not even in the workplace any longer, so that there is no obvious connection between the present task and the chronic injuries.

4.4 Chapter Discussion

4.4.1 Summary

In summary, the RASH model proposes that people willingly expose themselves to chronic injuries via a series of risk-taking processes. This causal chain starts with personal motivation and over-alignment with organisational purpose (including impression management). Ideally, motivation would be moderated by an ability to predict future harm consequences from the task at hand, but that mechanism is weak because it is difficult to predict cause and effect, the consequences are too far in the future, and opportunities for vicarious learning are few. The motivation then causes misdirected creativity, hence the development of personally novel ways of solving the problem, albeit with greater risk of harm. Perverse agency then sustains actions that exposure the person to harm.

4.4.2 Original Contributions

This work makes several novel contributions. Firstly, it offers a finer-resolution explanation of risk-taking activities in the organizational context. It explains the causality whereby people compromise their personal occupational health and safety. It does this by combining new and old concepts. It incorporates several well-established elements of psychology, namely motivation theory, personality, worldviews, self-efficacy, locus of control, dark triad, and ethics. It also uses the concept of organisational alignment, which is from strategic human resource management (SHRM) and organizational behavior (OB) more generally. Therefore, a second contribution is that these multiple disparate concepts have been integrated into a holistic model.

Several of the specific elements in this model are believed to be original. These include the proposed relationship between novelty and the risk perceived in a task (see the 2 × 2 matrix of Figures 4.2 and 4.3). Also, the concept of perverse agency has not previously been identified, although the agency of itself is a long-standing concept.

Existing models of harm causation include the following.

Domino theory [247]—This was developed by H.W. Heinrich in 1931 and proposed that accident happens in a sequence like dominoes knocking each other. He also described the cause factors to be social environment and ancestry, fault of the person, and unsafe acts [248]. In contrast, the RASH model focuses more on workers' motivation and decision making. Additionally, RASH includes more factors (especially elements from psychology). Moreover, our model has a specific focus on long term health consequences.

Reason's Swiss Cheese Model [249]—James Reason developed a dynamic model to describe the relationship between human factor errors and safety accidents [250, 251]. The model provides a general categorization of human errors into slips, lapses, mistakes, and violations. This has been useful and further developed and applied into the crew resource management (CRM) framework e.g., [208], and the barrier or the bowtie method [252-255]. The limitation of the Swiss Chess model and its derivatives is the inability to explain why the human factors occur in the first place. Additionally, this class of models describes the cause of accidents as a linear sequence of events. In contrast, the RASH model offers a more detailed explanation of the psychology that underlies the human factors. It also explicitly includes the cumulative exposure and long-term health issues, whereas those other methods tend to focus on accident causation.

In summary, when compared to existing models, the RASH model has the following features. Firstly, it includes more sub-components, especially elements from psychology. Secondly, it provides an integrative treatment in the way that it relates these factors together. Thirdly, it is particularly strong at describing the cognitive processes that contribute to the decisions made before the accident commences—in contrast, many other models focus on the physical sequence of the accident. Fourthly, it specifically includes the long-term harm effects. Fifthly, the RASH model focuses on how people make risky decisions, this is a generally decision-making focus, not a specific focus on one particular situation.

4.4.3 Implications for Practitioners

The model is particularly focused on the health and chronic harm component of H&S, as opposed to the accident or safety part. This is deliberate, because the chronic harm part is underrepresented in the safety literature as compared to the safety part. It is much easier in industry to address the safety part, because the consequences of an accident are immediately apparent. Many of the safety systems are built on that assumption of immediacy, e.g., accident and near-miss reporting systems. Consequently, the continuous improvement processes work quickly and effectively for safety, but only weakly for long-term harm. This work makes a contribution by proposing a set of mental processes in the mind of the worker at the moment of time before the harm occurs. By framing these in terms of standard psychological constructs (many of which have their own measurement instruments) it is hoped that future work may lead to a situation where workers can be trained to put aside these perverse antecedents and thereby avoid chronic harm. Obviously, we have not achieved that level of intervention, but it is hoped that the model moves the field forward by providing a candidate framework for how the incidence of chronic harm may be reduced.

Our tentative recommendations to employers would be to take more care about presenting organisational alignment in a balanced way. Most chief executive officers (CEOs) are motivated, intrinsically or by performance incentives, in order to maximise worker motivation towards the organisational purpose, hence alignment. A number of SHRM tools are available to achieve this. It is rare to see the OB literature acknowledge the possibility of over-alignment and identify the specific detriments thereof. Unethical behavior is known to be one such adverse outcome, and now we propose that long-term harm is another. If this is true, then it implies the necessity to use the SHRM tools in a more balanced way, so as not to recruit perverse agency. Thus, it is our belief that the problem of perverse agency, while occurring within the cognition of the worker, is fundamentally a problem of the organization and its culture, and consequently, a deficiency of leadership.

Regarding the conventional safety prevention framework of avoidance and minimization, the implications of the present work would be the following. For avoidance, we suggest that workers judge their capability more carefully at the decision-making stage before commencing work. We suggest that they attempt to de-bias themselves from excessive organizational over-alignment—possibly they might achieve this by considering themselves as professional operators who (a) are technical experts about the task and (b) intend to live a long life with high quality of life. For minimization, we suggest achieving this aim by (a) team support and (b) safety training. Team support refers to building a support system between teammates, e.g., tool-box talks [256]. This is not solved by recruiting a new safety team, but building a positive safety culture.

4.4.4 Limitations of the Work

The work is conceptual in nature, and the proposed causality is thus speculative. We have designed the model to improve the robustness, by including extant concepts from psychology where possible. However, this does not guarantee that the model is correct.

Another limitation is that we have designed the model from a pejorative perspective, i.e., of the worker who is taking a safety short cut. There are many other workers who do not behave in this way, and the model does not represent their actions.

4.4.5 Implications for Further Research

This work provides a broad framework within which are numerous implied relationships of causality. Future work could be directed to verify whether the sub processes do actually work as depicted, and what the conditional factors (contingency variables) might be. An interesting and useful feature of the flowchart model is that each activity block can be interrogated in this way. For example, in Figure 4.5, it is proposed that intrinsic motivation is some combination of several factors (personality, worldview, valance, expectancy, etc.). How strong are these individual contributions? This might be explored by seeking the correlation coefficients in a quantitative statistical study. Similarly, there are opportunities for qualitative research in the sub models, for example, to determine how workers make sense of their alignment with the organizational objectives. These qualitative aspects were not considered further in this thesis, as the work focussed on the integration of safety with production economics.

4.5 Chapter Conclusions

This Chapter developed a conceptual model for why workers expose themselves to health risks. It is proposed that harm arises from personal motivation and over-alignment with organisational purpose, which recruit misdirected creativity and perverse agency. Original contributions are the provision of a detailed explanation for risk-taking, and the integration of multiple well-established psychological constructs.

The perverse agency model helped the subsequent development of the thesis by identifying a different way of thinking about the violation of procedures. From James Reason's perspective the violation is failing of the human operator to follow defined organisational practices. From the perverse agency perspective, the failing could just as well be that the organisation has over-aligned the worker with its productivity objectives. Hence when we are examining the effect of human error on accidents and personal health, it is necessary to include the productivity aspects. This materially influenced our subsequent thinking and the way we went about developing the integration between safety assessment and plant simulation.

Chapter 5: Developing a Diminished Quality of Life Instrument to Measure Health and Safety Risks

This chapter contributes to the following publication:

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5.1 Chapter Introduction

Historically, the focus of industrial health and safety (H&S) has been on safety and accident avoidance with relatively less attention to long-term occupational health other than via health monitoring and surveillance. The difficulty is the multiple overlapping health consequences that are difficult to separate, measure, and attribute to a source. Furthermore, many health problems occur later, not immediately on exposure, and may be cumulative. Consequently, it is difficult to conclusively identify the cause. Workers may lack knowledge of long-term consequences, and thus not use protective systems effectively. Compounding this is the lack of instruments and methodologies to measure exposure to harm. Historically, the existing risk methodologies for calculating safety risk are based on the construct of consequence and likelihood. However, this may not be appropriate for health, especially for the long-term harm, as both the consequence and likelihood may be indeterminate. This paper develops an instrument to measure the health component of workplace H&S. This is achieved by adapting the established World Health Organization Disability Assessment Schedule (WHODAS) quality of life score to workplace health. Specifically, the method is to identify the likelihood of an exposure incident arising (as estimated by engineering technologists and H&S officers), followed by evaluation of the biological harm consequences. Those consequences are then scored by using the WHODAS 12-item inventory. The result is an assessment of the DQL associated with a workplace hazard. This may then be used to manage the minimization of harm, exposure monitoring, and the design of safe systems of work.

5.2 Approach

5.2.1 Purpose

The purpose of this research was to develop an instrument to measure long term health, suitable to be used as a method to manage the risks in the industry.

5.2.2 Methodology

Our approach was to identify the typical hazards in a manufacturing situation. Then, we determined the range of biological consequences for these, with a particular focus on the health issues. An initial hazards list was generated based on the literature [69] and health and safety legislation [32]. The specific area under examination for developing the hazards list was based on lathe work in a workshop. This list included items, such as 'Chemical Exposure'.

The literature concerning the potential biological consequences in the manufacturing industry was also examined from sources, such as the international classification of disease in occupational health (ICD) [70]. A list of biological consequences was developed together with the level of harm. This analysis was related to the particular type of machine operation under examination. Examples of items on this list are 'Skin Disease, Respiratory System Compromised, Blood Pressure Compromised, etc.'

The next challenge was to link the hazards with the biological consequences. This is a many-to-many correspondence. This link was demonstrated using an ontology, using the "Protégé" software. This expressed the multiple biological consequences associated with the hazards.

Subsequently, we needed a measurement of harm. For this, we adopted the established WHODAS quality of life score. We applied the WHODAS questionnaire to each of the biological consequences to determine the quality of life consequences of such a biological event.

Finally, we needed a framework to link these components into a coherent system that might be used to manage health in the workplace. We found that the conventional risk assessment methodology, with its strict demarcation between consequence and likelihood of the consequence, was unhelpful. Instead, we devised a new framework, which inverts the conventional process. It starts with the likelihood of an exposure incident arising (as estimated by engineering technologists and H&S officers), followed by evaluation of the likelihood of biological harm consequences in the situation (as evaluated by an occupational hygienist). The rest of the process is then mostly automatic, since it uses the previously established WHODAS scores. It results in a quantitative measure of the adverse effects of the work activities on the quality of life of the worker.

We call this the DQL metric. It is not the same as the conventional risk assessment method, and the results must be interpreted differently. See Section 5 for a discussion comparing the methods. We propose a set of thresholds and associated preventative mechanisms.

The DQL method is then applied to a case study.

5.3 Results

5.3.1 The Conceptual Model

The dominant paradigm for risk assessment is per the ISO 31000 process that partitions risk into consequence and the likelihood of that consequence. If we are to find better ways of incorporating the long-term health component into the assessment, then it will be necessary to re-conceptualise harm. Consequently, we developed a new conceptual framework, by starting with the biological consequences and working backwards to connect those causally to the hazards that might cause them, and how to represent them.

The hazards were classified by following a review of existing research. The objective was to address hazards for both health and safety, and with a special focus on the hazards that may result in long-term effects. Health and safety incident descriptions were identified for each hazard along with the corresponding biological consequences. The three steps in designing this conceptual model are shown in Figure 5.1.

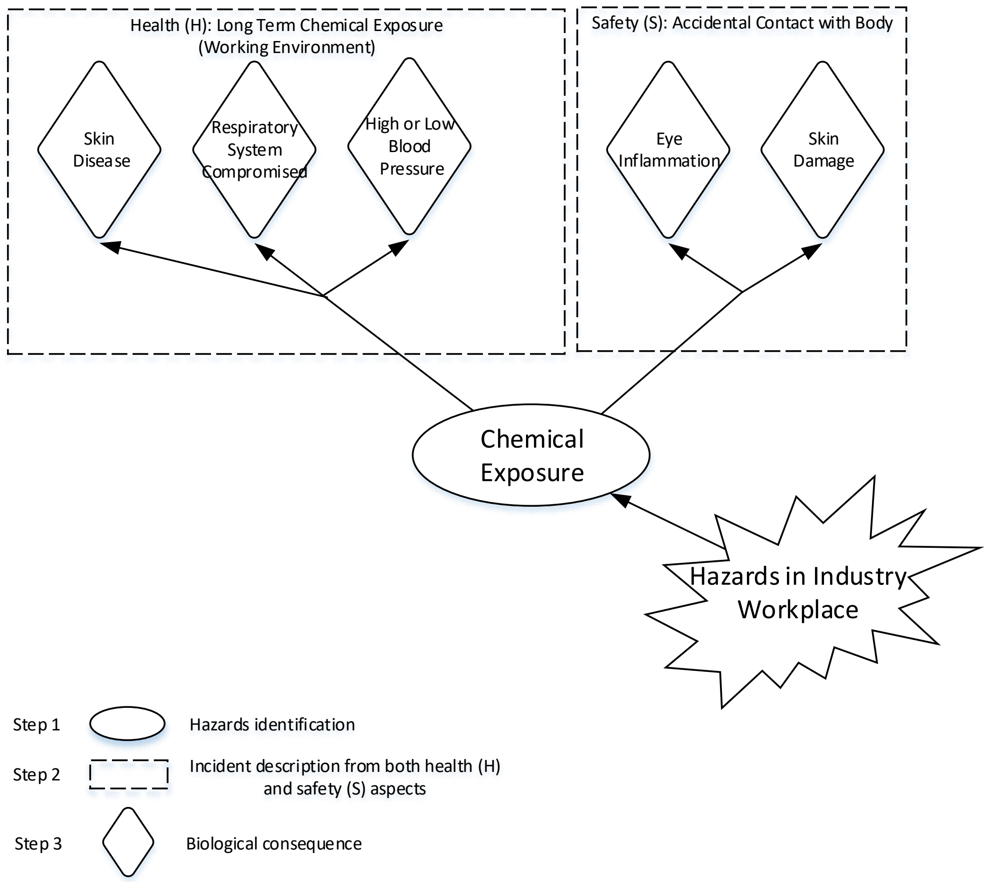

Figure 5.1. The three steps in designing the conceptualization model.

The literature review showed that each hazard has potentially multiple effects on a person's health. For example, chemical exposure can have negative effects on a person's body not only due to long-term exposure, but also by short term exposure, such as accidental contact. Chemical exposure can cause potential harm to a person's health by cumulative exposure, for example, skin disease, respiratory system harm, and high or low blood pressure. It also can cause harm to the body by accidental contact, and, consequently, result in damage, such as acid burn.

Health needs to be treated differently to safety. This is because of their unique characteristics. Safety problems are related to accidents, and they can affect a person's body immediately. By contrast, health problems are more likely to occur after a period of time, or by cumulative exposure with an associated accumulation/incubation period. Furthermore, compared to safety, some health problems can be hard to cure, or cannot be cured, and thus result in chronic issues. Therefore, we propose to classify hazards as either health or safety.

5.3.2 Health and Safety Hazards List

Based on the existing literature, manufacturing industry hazards are of two types: **Environmental hazards** and **machinery hazards**. A list of such health and safety hazards was aggregated from multiple sources, e.g., Health and Safety Executive (HSE) , UK [257], WorkSafe NZ [258], and Occupational Safety and Health Administration US (OSHA) , US [259].

The environmental hazards in the manufacturing industry are grouped as chemical exposure, dust environment, light, noise, trips and falls, and temperature.

- ***Chemical Exposure:*** Chemical exposure can result in an accident or a long-term health problem. Chemicals can come in contact with the skin and eyes, resulting in skin damage [260] and eye injury [261]. Chemicals can also cause respiratory system problems [262]. Exposure to chemicals can be fatal [263].

- ***Dust:*** Machining operations can cause dust at work, such as cutting carbon and wood. This may result in breathing difficulties and lung disease [264, 265], especially when inhaled for a long time [266].

- ***Light:*** Activities, such as cutting and welding, can have light issues associated with them. The consequence can be eye strain and short sightedness [267]. The light in welding activities can be very strong, and lack of eye protection can result in blindness.

- ***Noise:*** Noise is a general hazard in the manufacturing industry due to the nature of manufacturing operations [268, 269]. The consequence of long term expose to relatively high noise levels can result in hearing loss [270].

- ***Slips, trips, and falls:*** Slips can be caused by inadequate cleaning, e.g., uncleaned and undried water on surfaces [43]. Trips can be caused by unsecured equipment, e.g., cables [271]. Falls from a height can be caused by loss of function of PPE, e.g., improper footwear [272, 273]. The biological consequence of slips, trips, and falls can be bruises, abrasions, sprains, fracture, and even death [274].

- ***Temperature:*** Temperature can be uncomfortable in the manufacturing industry, as some products are created by using high or low temperature, e.g., tyres. High temperatures in the work environment can cause circulatory system diseases, e.g., blood pressure problems. Low temperatures can result in muscle fatigue [275].

Machinery hazards in the manufacturing industry include cutting, crushing and squashing, electrical damage, heat and radiation, impact damage, wearing loose cloth, manual heavy loads, doing repetitive work, ventilation, vibration at work, and working in an uncomfortable position.

- ***Cutting, crushing, and squashing:*** Manufacturing industry activities can result in cutting and squashing, for example, by operating machines (e.g., a lathe) and using hand tools (e.g., a hammer). The consequence of the associated hazards can be abrasion, small cuts, fracture, amputation [276], and even death [273].

- ***Electrical damage:*** Electricity can result in serious harm to a worker in the manufacturing industry [41],[277]. An electrical burn can cause skin damage [278], and a serious electrical shock can cause paralysis and even death [279].

- ***Entrapment:*** Loose clothes and working with machines can result in machines jamming or clothing touching hot surfaces (resulting in burns), and slips and falls [274]. This may then result in squashing, amputation, burns, and fractures.

- ***Heat and radiation:*** Heat and radiation can result in burns due to fire, hot objects, and hot liquid [42]. This can be fatal [280] [281, 282].

- ***Infection***: Infection is caused by bacteria and viruses [283]. In factories, infection can be caused through multiple ways, for example, a wound caused by impact damage, or a cut caused by sharp edges. In meat and seafood process factories, infections may be also caused by zoonosis [284].

- ***Impact:*** Impact damage to a worker can be caused by machines and moving vehicles, such as forklifts [285]. The biological outcome can be bruises, abrasions, sprains, fracture, paralysis, and even death.

- ***Manual heavy loads:*** Manual heavy loads in the manufacturing industry can be caused by moving heavy products, and operating machines. A person who suddenly moves a heavy object can get muscle injury, resulting, for example, in back pain [273]. Heavy manual work can result in musculoskeletal damage, such as tendinitis and fibromyalgia.

- ***Repetitive work:*** Manufacturing work can be characterised by repetitive activities, such as packaging. Long term exposure to this hazard can result musculoskeletal damage [24].

- ***Ventilation:*** Fresh air provides a healthy working environment for workers, and this can be contributed by ventilation [286]. Poor ventilation may result from lack of oxygen, and this can lead to dizziness; it may also lead to an uncomfortable temperature [287] [288]. It may contribute to a lack of attention, and hence exposure to other hazards. Welding in confined spaces can be particularly dangerous.

- ***Vibration:*** Vibration can be caused by machinery and equipment at work, e.g., drilling equipment [289]. The biological outcome of this hazard can be musculoskeletal damage [23].

- ***Uncomfortable working position:*** Work in an uncomfortable and awkward position may happen when the height of the work surface is not appropriate for someone [24]. It can happen when workers are asked to hold an object at an overhead height [290].

This is an ergonomic issue and may result in muscle strain and musculoskeletal damage [291].

A hazards list was created, combining both environmental hazards and machinery hazards. The various hazards were sorted alphabetically, and are shown in Table 5.1. This hazard list is considered to be comprehensive, but can be customised.

Manufacturing Industry Hazards List:
1. Chemical Exposure
2. Cutting, Crushing, and Squashing
3. Dust
4. Electrical Damage
5. Entrapment
6. Heat and Radiation
7. Impact Damage
8. Infection
9. Lighting
10. Manual Heavy Loads
11. Noise
12. Repetitive Work
13. Slips, Trips, and Falls
14. Temperature
15. Uncomfortable Work Position
16. Ventilation
17. Vibration at Work

Table 5.1. Manufacturing industry hazards list.

5.3.3 Biological Consequences

Health related biological outcomes in the manufacturing industry were identified based on the international classification of disease in occupational health (ICD) [292] and the international classification of functioning, disability, and health (ICF). These are infectious diseases [292], malignant diseases [293], blood disease [294, 295], mental and behavioural disorders [296, 297], nervous system disease [298], eye disease [299, 300], ear disease [10, 301], circulatory system disease [302], respiratory system disease, and musculoskeletal system disease [24]. The incubation period can be very long, or may occur by cumulative exposure, hence they can be difficult to detect [303]. Additionally, because of individual physique, the consequence of harm may be different. The consequences of health harm can be influenced by a number of factors, such as gender [304] and age [46, 305].

In contrast with health, safety accidents usually cause immediate personal harm to the human body. Transportation equipment, such as conveyors, forklifts, and trucks, may also result in impact damage to workers [39]. The biological outcome of machinery accidents may result in amputation [306], laceration [307], fracture [308], and even death [309]. Other possible harms are cuts and bruises [310]. Some other harms are caused by environmental accidents, such as trips and falls, chemicals [311], and electrical discharges [312]. Some of the environment accidents, like fire, can cause significant damage, even death [313].

Once all potential biological consequences in the manufacturing industry were identified, a health consequences list was generated based on the literature, and this is presented in Table 5.2. We propose the consequence is different for different body parts. Hence, for example, amputation was divided into five categories: Arms, fingers, foots, hands, and legs. The various consequences list is presented by level. The application of the framework is limited to the second level. This is because further work is necessary to establish the lower level consequences with confidence.

Biological Consequences:			
1.	Abrasions and Lacerations		
	a.	Abrasions	
		i.	Minor Abrasion
		ii.	Extensive or Deep Lacerations Leading to Scarring
	b.	Lacerations	
		i.	Minor Laceration
		ii.	Soft Tissue Damage (Surgical Intervention)
		iii.	De-gloving Accident
2.	Amputation		
	a.	Amputation of Arm	
	b.	Amputation of Finger	
	c.	Amputation of Foot	
	d.	Amputation of Hand	
	e.	Amputation of Leg	
3.	Blood Pressure Compromised		
	a.	High Blood Pressure	
	b.	Low Blood Pressure	
4.	Cardiovascular Disease		
	a.	Heart Disease	
	b.	Blood Vessels Disease	
5.	Death		
6.	Eye injury		
	a.	Foreign Object in Eye	
	b.	Damage to Cornea	
	c.	Partial Loss of Sight	
	d.	Loss of One Eye	
	e.	Loss of Both Eyes	
	f.	Eye Fatigue	
7.	Hearing Loss		
	a.	Auditory Processing Disorders	
	b.	Conductive Hearing Loss	
	c.	Sensorineural Hearing Loss	
	d.	Mixed Hearing Loss	
8.	Infections		
	a.	Wound Infection	
	b.	Animal Infectious Diseases	
9.	Musculoskeletal Injury		

	a. Bruise to Soft Tissue
	i. Localised - Minor
	ii. Severe
	iii. Organ Bruising
	b. Muscle Damage
	i. Temporary Fatigue
	ii. Muscle Micro Tear
	c. Tendon and Ligament Injury
	i. Sprain
	ii. Dislocation
	iii. Tearing
	iv. Detachment
	d. Bone Injury
	i. Incomplete Crack
	ii. Fracture of Digits
	iii. Fracture Requiring Splinting
	iv. Fracture Requiring Cast
	v. Fracture Requiring Surgical Setting
	vi. Fracture Requiring Surgical Fixation (Metal Plates)
	e. Head Injury
	i. Concussion
	ii. Bone Damage
	iii. Neurological Damage
	f. Musculoskeletal Disease
	10. Paralysis
	a. Monoplegia
	b. Hemiplegia
	c. Paraplegia
	d. Quadriplegia
	11. Respiratory System Compromised
	12. Skin Harm
	a. Skin Damage
	i. Acid Burn
	ii. Physical Wound
	b. Skin Disease
	i. Dermatitis
	ii. Acne

Table 5.2. Biological consequences.

5.3.4 Linking the Hazards to the Biological Consequences

The relationships between hazards and biological consequence were then identified. The relationships are complex. A hazard can result in multiple consequences; a consequence can also be caused by different hazards. Therefore, an information methodology was adopted using an ontology. An ontology describes the relationship and hierarchy between each hazard and the corresponding biological consequence. Additionally, the ontology also focuses on processing and grouping similar consequences into categories. We applied Protégé software to map the lists of hazards and biological consequences. The relationship was then expressed by using mapping analysis. See Figure 5.2 for an example of the relationship between safety hazards and muscle damage, and cardiovascular disease.

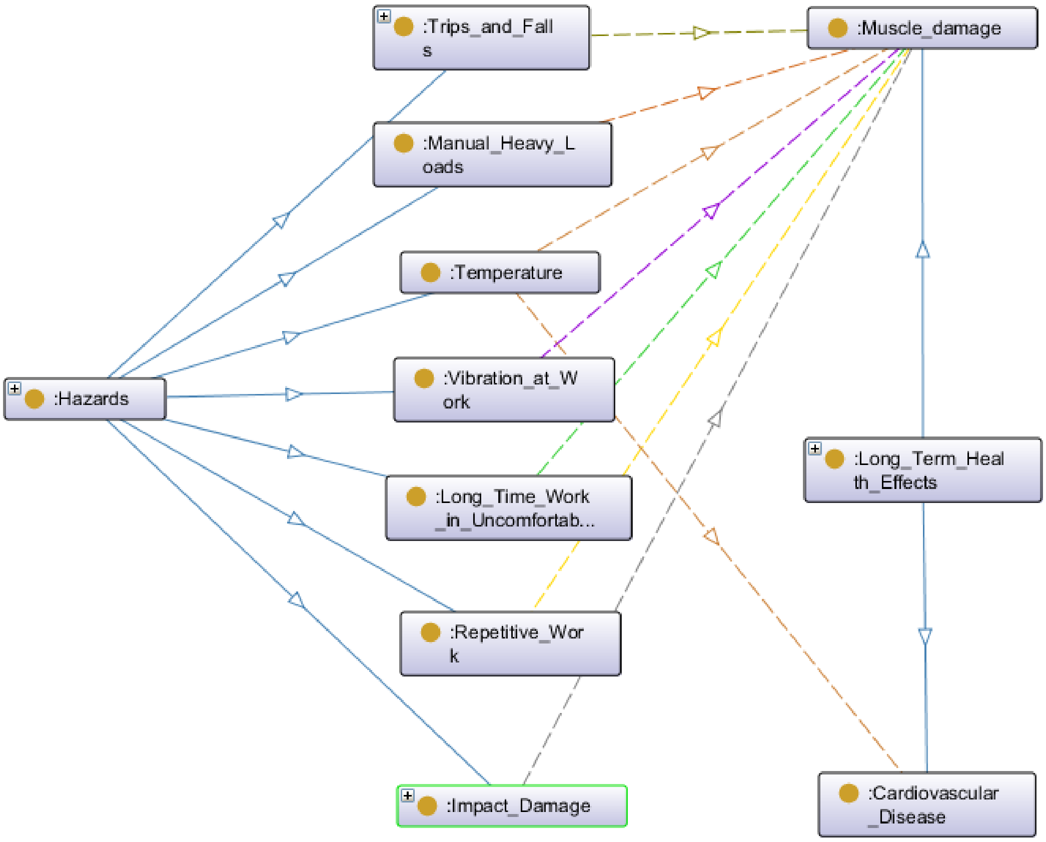

Figure 5.2. Relationship between safety hazards and biological consequences in Protégé.

The benefit of using the ontology is that it imposes a systematic process for ensuring the coherence of the model. We found this helped ensure that biological consequences were less likely to be overlooked.

In practice, the way the ontology is expected to work is that the hazards would be identified in the workplace (e.g., ‘chemical exposure’), and the ontology would then automatically identify the associated biological consequences (e.g., skin disease, respiratory system problem, blood pressure problem, eye injury, skin damage). An occupational hygienist would identify the frequency of these consequences arising in the situation. Possibly, the ontology could also support decision-making at this latter step by providing default estimates. In the present work, the ontology is not fully automated in the software, instead the process requires manual input of data via a spreadsheet. Nonetheless, we believe that the overall architecture shown here should be feasible to deploy in the software.

Based on the result of the relationship map, we then developed a register to express the casualty of hazards and biological consequences, see Table 5.3 (H: Health; S: Safety.). The casualty was developed based on the existing literature.

Hazards in Workplace	**Incident Description** *(S: Safety Accident H: Health Issue)*	**Biological Consequence**
Chemical Exposure	H: Long term chemical exposure in work environment	Skin disease, e.g., dermatitis
		Respiratory system compromised
		Blood pressure compromised
	S: Exposure to eye	Eye injury
	S: Exposure to skin	Skin damage
Cutting, Crushing, and Squashing	S: Accidentally injured by machine	Amputation (arm, finger, foot, hand, and leg)
		Lacerations
		Bone injury
		Death
	S: Accidentally injured by hand tools	Abrasion
		Amputation (arm, finger, foot, hand, and leg)
		Bone injury
	S: Accidental bodily injury by foreign objects	Lacerations
	S: Accidental eye injury by foreign objects	Eye injury
Dust	H: Dust in lungs	Respiratory system compromise
Electrical Accident	S: Electrical burn	Skin damage
	H: Electrical shock	Skin damage
		Paralysis
		Death
Heat and Radiation	S: Burn via fire, hot object, hot liquid, hot vapour	Eye injury
		Skin damage

Hazards in Workplace	Incident Description *(S: Safety Accident H: Health Issue)*	Biological Consequence
Impact Damage	S: Workers hit by machine, forklift, and other objects	Musculoskeletal injury
Impact Damage	S: Workers hit by machine, forklift, and other objects	Abrasion
Impact Damage	S: Workers hit by machine, forklift, and other objects	Bone injury
Impact Damage	S: Workers hit by machine, forklift, and other objects	Lacerations
Impact Damage	S: Workers hit by machine, forklift, and other objects	Skin damage
Impact Damage	S: Workers hit by machine, forklift, and other objects	Paralysis
Impact Damage	S: Workers hit by machine, forklift, and other objects	Death
Lighting	H: Uncomfortable or strange light in workplace	Eye fatigue
Entrapment	S: Get caught by machine	Amputation (arm, finger, foot, hand, and leg)
Entrapment	S: Touch hot surface	Skin damage
Entrapment	S: Trips, slips and falls	Abrasion
Entrapment	S: Trips, slips and falls	Musculoskeletal injury
Entrapment	S: Trips, slips and falls	Lacerations
Entrapment	S: Trips, slips and falls	Eye Injury
Entrapment	S: Trips, slips and falls	Bone injury
Entrapment	S: Trips, slips and falls	Paralysis
Entrapment	S: Trips, slips and falls	Death
Manual Heavy Loads and Repetitive Work	H: Moving heavy tools, machines, and other objectives; or long-time repetitive work, e.g., packaging	Muscle damage, tendon, and ligament injury
Noise	H: Caused by machine operating	Hearing loss
Temperature	H: Uncomfortable temperature Environment	Circulatory system diseases
Temperature	H: Uncomfortable temperature Environment	Musculoskeletal injury
Ventilation	H: Uncirculated air	Respiratory system compromise

Hazards in Workplace	**Incident Description** *(S: Safety Accident H: Health Issue)*	Biological Consequence
Vibration	H: Long term vibration exposure	Muscle damage, tendon, and ligament injury
Uncomfortable Working Position	H: Long term work in uncomfortable position	Muscle damage, tendon, and ligament injury

Table 5.3. Hazards and biological consequences.

5.3.5. Adoption of a Quality of Life Scale

Level of harm is a key factor in illustrating the negative effects to the human body. However, it is very hard for people to measure the level of harm. The first reason is that some health problems are chronic and this then results in uncertain consequences. Secondly, some health problems may have a long incubation period or affect the human body slowly, hence attribution to a specific time or event may be difficult. Hence, this may then result in uncertain consequences, weak protections, and late treatments. Thirdly, the level of harm is also dependent on a person’s physical ability. Therefore, we propose to use the Quality of Life (QOL) methodology to address the level of harm.

QOL was defined by the WHO in 1948 as “*a state of complete physical, mental, and social well-being, and not merely the absence of disease*” [314]. There are many QOL measuring instruments developed by different researchers, e.g., the Karnofsky Performance Scale, Sickness Impact Profile, and linear analogue self-assessment (LASA) methods [314]. However, these are focused on medical aspects, and QOL in the manufacturing industry are weakly applied and developed. The WHO also have a quality of life score, the WHO Disability Assessment Schedule (WHODAS 2.0) [114]. We assessed this as more relevant to the situation of industrial harm. There are three different instruments developed by WHODAS, and we decided to use WHODAS 12-item instrument [114]. This is more focused on physical effects than the other two instruments. It was developed to identify how much difficulty a person has in completing the tasks of daily living. The WHODAS questions are shown in Appendix B. Each WHODAS 12-item has a 0 to 4 scale, see Table 5.4. The results are percentages, and are used to express the level of physical ability. A higher score indicates higher disability.

When using WHODAS the following numbers are assigned to the response
0 = No Difficulty
1 = Mild Difficulty
2 = Moderate Difficulty
3 = Severe Difficulty
4 = Extreme Difficulty or Cannot Do

Table 5.4. WHODAS scales.

5.3.6. WHODAS Scores for Manufacturing

We then applied the WHODAS to a lathe work process, as representative of a common manufacturing industry activity. Potential hazards in operating a lathe were identified, see Figure 5.3.

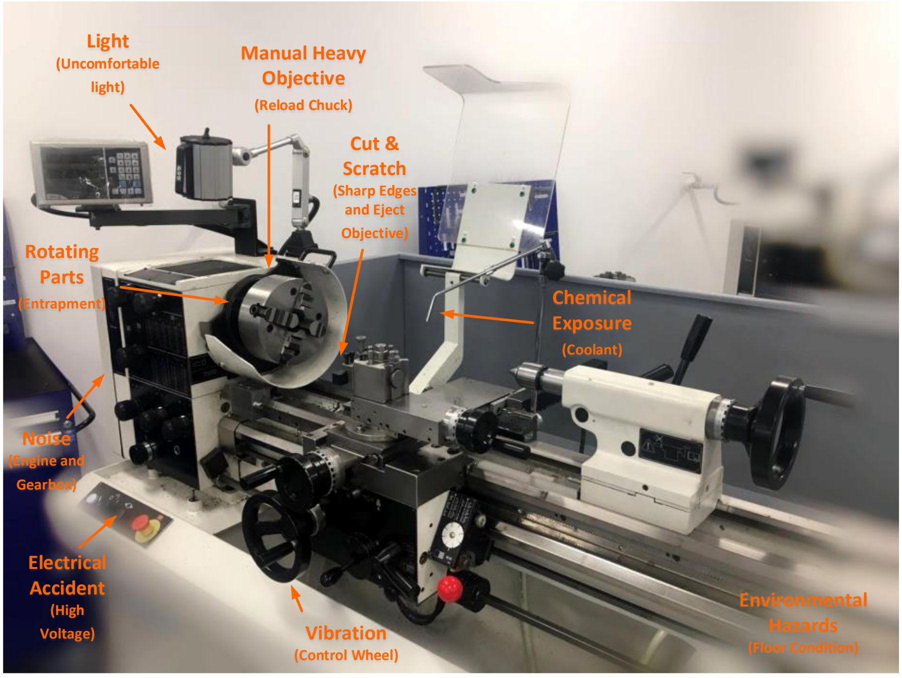

Figure 5.3. Lathe machine hazards.

In this type of work, workers are exposed to both environmental hazards and machinery hazards. A typical environmental hazard here is hearing loss. Some other typical machinery hazards are cuts by the machine and contact with chemical products (e.g., coolant). The biological consequence for a cut may result in laceration and in extreme cases amputation; and the chemical exposure may potentially result in skin disease. We classified all potential hazards and their biological outcomes, and for each, we determined the WHODAS score. Representative data were used to demonstrate the principle. In this way, we determined the diminished long-term quality of life due to the exposure to say coolant. The WHODAS results for the lathe work are shown in Table 5.5, (see also Appendix B).

Question Number	Q1	Q2	Q3	Q4	Q5
Hazard Description	Standing for long period, such as 30 minutes?	Taking care of your household responsibility?	Learning a new task, for example, how to get a new place?	How much of a problem did you have in joining in communitiy activities (for example, festivities, religious or other activities) in the same way as anyone else can?	How much have you been emontionally affected by your health problems?
Abrasion	0	0	0	0	0
Amputation (Arm)	0	4	0	2	2
Amputation (Finger)	0	1	0	0	1
Amputation (Foot)	3	3	0	1	2
Amputation (Hand)	0	4	0	1	2
Amputation (Leg)	4	4	0	2	2
Tendon and Ligament Injury	0	1	0	0	0
Blood Pressure Problem	1	1	0	2	0
Bruise to Soft Tissue	0	0	0	0	0
Cardiovascular Disease	1	0	0	2	0
Death	4	4	4	4	4
Eye Injury	0	4	3	3	3
Eye Fatigue	0	1	1	1	1
Fracture	2	3	0	3	2
Hearing Loss	0	0	1	1	1
Lacerations	0	0	0	1	1
Muscle Damage	2	2	0	0	1
Musculoskeletal Disease	1	1	0	0	1
Paralysis	4	4	0	4	3
Respiratory System Problem	0	0	0	1	0
Skin Damage, e.g.acid burn	0	0	0	0	1
Skin Disease, e.g. dermatitis	0	0	0	0	1
Tendon and Ligament Injury	1	1	0	0	0

Table 5.5. WHODAS score for lathe work.

5.3.6 Likelihood of an Incident Arising

Probability and frequency can be used to express the likelihood of an incident. Sherman Kent in 1964 presented the idea of Words to Estimate Probability (WEP) [315]. This is widely used in likelihood descriptions. Some popular WEP words are ‘certain’, ‘possible’, and ‘impossible’. This has been applied to risk research, and the likelihood scales were developed using qualitative words [111]. Sherman Kent also proposed that there are differences between “poets” (people preferring to use wordy descriptions in probability) and “mathematicians” (people preferring to use quantitative methods) [316].

We propose to use a quantitative number to express the probability and frequency, instead of qualitative words. This is because we intend to get a numerical result in health and safety risk. A likelihood diagram was developed by the Central Intelligence Agency (CIA) in 2007 [317], see Table 5.6. We adapted this, as further described below.

Qualitative Description	Numerical Probability
Certain	100%
Almost Certain	93% (Give or Take About 6%)
Probable	75% (Give or Take About 12%)
Chances About Even	50% (Give or Take About 10%)
Probably Not	30% (Give or Take About 10%)
Almost Certainly Not	7% (Give or Take About 5%)
Impossible	0%

Table 5.6. Likelihood scale (adapted from CIA, US).

We developed and adopted a scale for the estimated frequency and likelihood by modifying the CIA scale in discussion with engineering technicians. The results are shown in Table 5.7.

Descriptor	Description of frequency	Probability
Almost Certain	Annual occurrence in the situation	90%
Likely	Has Occurrence several times in a person's career life	60%
Possible	Might occur once somewhere from time to time	50%
Unlikely	Event does occur somewhere from time	30%
Rare	Heard of something like this happened	7%
Almost Incredible	Theoretically possible but not expected to occur	1%

Table 5.7. WEP-likelihood scale diagram.

5.3.7 Proposed Instrument for DQL

We now present a new concept that integrates all the above. We propose that health effects of industrial activities be measured as 'diminished quality of life'. DQL refers to the extent to which a hazard has a biological consequence that adversely affects a person's quality of life much later in life. The DQL measurement is quantitative, ranging from 0 to 100. 0 refers to no negative effects on a person's life, and 100 refers to a very bad outcome, like death.

DQL can be calculated in a four-step process. First is identifying the likelihood of incidents, see Section 4.5.1. Second is identifying the likelihood of a biological consequence. Third is identifying the level of harm: This is done through WHODAS, see Section 4.3.2. Finally, DQL can be calculated using equation (1):

$$DQL_{Total} = \sum_{i}^{n} F_i L_c C_i \tag{1}$$

DQL_{Total}: Diminished total quality of life in total;

F_i: Frequency of a single incident arising in a working career at this site;

L_c: Likelihood of the consequence arising;

C_i: Consequence of the biological outcome of the incident ;

n: The number of hazards; and

i: The number of incidents arising with harm.

We propose that DQL can be used for both long term health effects and short term safety accidents. It can potentially also be used in H&S management across other industries, such as construction. However, this paper is focused on DQL in the manufacturing industry. The DQL result of lathe operating has been addressed in Appendix B.

5.3.8 Evaluation of Severity of Consequences for Quality of Life

After collecting the result of DQL, a method is proposed for workers to determine the overall outcome in health and safety. There is a need to determine thresholds for action, i.e., DQL scores that warrant treatment of the hazard. This is a difficult problem because the long-term biological consequences are poorly understood. Nonetheless, there is a need to develop guidelines for practitioners, so that they can target their finite resources towards appropriate interventions.

To determine the thresholds for action, we analysed the DQL result of lathe operating as representative of a typical material removing (cutting) process in manufacturing. It was noted that 51% of results were between 0-1. We inferred this as an acceptable score, on the basis that the lathe technology is widely used, and this level of residual risk appears to be accepted by industry: There appears to be an acceptance or assumption of risk at this level. We propose that items scoring 1 or lower are low level and may be inconsequential. They are indistinguishable from background risk factors in society generally. This category includes, for the lathe case, e.g., 'Blood Pressure Problem', and 'Respiratory System Problem'. (In different situations, these may be more important.)

It was noted that 29% of DQL results were between 1-3 for the lathe. We propose that a DQL result between 1-3 is a moderate level. This applies in the lathe case where the current safety preventions are considered good. Some of the 'Musculoskeletal Injury' risks appear to be in this category for lathe work.

A further 20% of results were between 3-8. We propose a DQL result between 3-8 be considered a high level, and more attention should be given to implementation of treatments. For the lathe work, these were identified as hearing loss and eye injury.

Additionally, the DQL result can, in principle, be over 8, though no such levels were evident for the lathe process. Hence, we propose that a DQL result over 8 is at the extreme high level, and has an unacceptable risk, requiring urgent treatment.

It is acknowledged that these thresholds are subjective. The above strategy is summarized in Table 5.8, along with the recommended preventative mechanisms.

DQL Result	DQL Level	Preventative Mechanisms
0-1	Low	No further treatments required.
1-3	Moderate	Implement treatment in a reasonable time period.
3-8	High	Implementation of treatment required.
Over 8	Extreme High	Unacceptable risk. Need urgent treatment.

Table 5.8. DQL result.

There are several advantages in adopting a DQL instrument. Firstly, through analysing the result of DQL, workers can get a better understanding of safety hazards and biological consequences, especially of the long-term health effects. Workers can also identify the DQL level and determine reasonable preventative mechanisms. This results in better recognition of health and safety at work, hence improving prevention and recovery treatments.

5.3.9 Health and Safety Measuring Instrument- DQL Instrument

The practical implementation of the DQL instrument may be achieved in a spreadsheet or table, see Figure 5.12. The instrument consists of eight columns (A to H). Column A describes hazards in the workplace. Columns B is a description of the severity context and the current state. Column C is designed for a specific description of each hazard and relates to how someone could be harmed. Column D is for estimated frequency at work. Column E illustrates the corresponding biological consequence. Column F is the likelihood of the consequence. Column G is the corresponding WHODAS score. Column H is for calculating the DQL result, which is the product of columns D, F, and G.

This instrument is designed to be completed by engineering technologists, H&S officers, and occupational hygienists. Column B and Column D are designed for an engineering technologist to fill in. We assume that engineering technologists have a clear understanding of hazard identification and the frequency thereof. Column F is designed for H&S officers or occupational hygienists to fill in, as they are expected to have a good knowledge of occupational health and safety and also have the ability to present a reasonable likelihood based on analysing the incident reports.

For the full edition of the instrument with an application in lathe work, see Appendix A. An extract is shown in Table 5.9. According to results of the application in lathe work, 51% of results were between 0-1 (Low Level), 29% of results were between 1-3 (Moderate Level), 20% of results were between 3-7 (High Level), and 0% of the results were over 8 (Extreme High level). We then found that the high level DQL results were associated with amputation, laceration, eye injury, hearing loss, and death. Clearly, these need to have preventative treatments applied, hence it would be recommended for inclusion in a safe-work plan. Note that some of these outcomes (such as hearing loss) are in the long-term harm category, while others (such as amputation) are in the immediate accident category.

Diminished Quality of Life (DQL) Instrument							
A	B	C	D	E	F	G	H
Standard hazard categorisation, used as checklist by industry	*Severity Context is added by engineering technologist*	*Sub-category of column A per ontology*	*Estimate provided by engineering technologist or H&S officer*	*Sub-category of column C per ontology*	*Estimated by Occupational Hygienist or H&S officer*	*Derived from WHODAS*	*Computed (DxFxG)*
Hazards in Workplace	**Severity Context and current state**	**Incident Description** *(S: Safety Accident H: Health Issue)*	**Frequency of a single Incident arising in your working career at this site (Estimated for the workplace)**	**Biological Consequence**	**Likelihood of Consequence arising (Estimated for this workplace)**	**Consequence: Level of Harm (WHODAS)**	**Diminished quality of life (DQL)**
Chemical Exposure	Coolant and lubricating oil	H: Long term chemical exposure work environment	60%	Skin disease, e.g. dermatitis	50%	2.08	0.62
				Respiratory system compromise	30%	2.08	0.37
				Blood pressure compromise	7%	10.42	0.44
		S: Exposure to eye	30%	Eye injury	60%	12.50	2.25
		S: Exposure to skin	60%	Skin damage	50%	2.08	0.62
Cutting, Crushing and Squashing	Machine tools, open (not enclosed)	S: Accidentally injured by machine	50%	Amputation (arm, finger, foot, hand, and leg)	30%	47.92	7.19
				Lacerations	50%	14.58	3.65
				Bone injury	30%	17.92	2.69
				Death	7%	100.00	3.50
		S: Accidentally injured by hand tools	30%	Abrasion	50%	0.00	0.00
				Amputation (arm, finger, foot, hand, and leg)	7%	47.92	1.01
				Bone injury	30%	47.92	4.31
		S: Accidental bodily injury by foreign objects	50%	Lacerations	30%	14.58	2.19
		S: Accidental eye injury by foreign objects	30%	Eye injury	30%	64.58	5.81

Table 5.9. DQL health and safety measuring instrument applied to lathe work.

5.4 Chapter Discussion

5.4.1 Summary

Health Consequences

In summary, the DQL measuring instrument presents a new way to manage health and safety in manufacturing industries, especially the health component. This is achieved by adapting the established WHODAS quality of life score to workplace health. Specifically, the method is to identify the likelihood of an exposure incident arising (as estimated by engineering technologists and H&S officers), followed by evaluation of the biological harm consequences. Those consequences are then scored by using the WHODAS 12-item inventory. The result is an assessment of the Diminished Quality of Life associated with a workplace hazard. This may then be used to manage the minimization of harm, exposure monitoring, and the design of safe systems of work.

In doing this, our premise is that the ‘health’ component of H&S does not always have immediate consequences, but rather effects occur at some indeterminate point in the future. Once the harm does occur, it can often be too late for full cure. We propose that for these hazards, the lack of any immediate harm and the indeterminateness of the consequences contributes to a worker inadvertently assuming a degree of personal risk. Hence, self-prevention is undermined by the worker’s perverse agency [107].

Comparison between Risk Management and DQL Methods

We propose that the existing risk management methodology [4], with its focus on consequence and likelihood, is adequate for safety accidents that have an immediate and tangible consequence, but less so for the long-term harm hazards. The conventional risk assessment process per ISO 31000 encapsulates the concept that the assessment first identifies the consequences, and then the likelihood of those consequences, and then combines them with a product relationship. It is the indeterminate nature of both the consequences and likelihood that limits the risk assessment method in these cases. The product of two uncertain variables further increases the uncertainty in the outcome. We propose that it is intrinsically difficult for industrial risk assessors to make these evaluations reliably. It is difficult for people to anticipate the consequences of the present exposure on their health at some remote point in the future.

Hence, we make the somewhat radical proposal that the risk management methodology is intrinsically unsuited for the harm category of hazards. Instead, we propose that it could be more useful to get people to think about how the hazard might decrease their future quality of life. In doing so, we have borrowed and adapted a validated quality of life instrument used in medicine and rehabilitation. In the DQL methodology, the outcome is measured as a diminished quality of life and is the product of the frequency of exposure, the likelihood of long and short term biological consequences arising, and the WHODAS score for those consequences. While these frequencies and likelihoods are also subjective, the use of the WHODAS provides a measure of consistency, and frames the cognition process in the hazard assessment to be future-focused.

We propose that the two methods are complementary—they achieve different things. In both cases, the results of applying the methodologies are numerical outcomes, which can usefully contribute to health and safety management. The conventional risk management methodology may be ideal for risks that can be reliably quantified, e.g., financial, insurance, technical systems. It is also a simple and useful, even if imprecise, method for assessing accident risk when using simple scales for the two axes. We propose that risk assessment is an important first analysis tool: It causes people to be mindful of the hazards in a situation, and encourages the deployment of preventative treatments. It also provides a means to do due diligence to legal requirements, such as [64]. We suggest that methods based on quality of life, such as the DQL developed here, should be applied as a second stage of evaluation, as part of the continuous improvement process.

5.4.2 Original Contributions

This work makes several novel contributions. Firstly, it offers a systematic categorisation of health and safety hazards, and specifically addresses long-term health effects, including biological outcomes and their cause. This could potentially help workers better understand occupational health, and help managers provide safer work places.

Secondly, a conceptual framework has been developed around diminished quality of life to present health in a different way to the conventional risk management methodology. This has the potential to enrich the safety field, since health risks are otherwise difficult to analyse and manage. Thirdly, a methodology has been developed to provide a means to quantify DQL in an industrial setting. The DQL instrument not only addresses the accidental harm (environmental and physical) in the manufacturing industry, but also has a special focus on long-term health effects. The biological outcome and its cause are also addressed. The method relies on estimates that are feasible to obtain in the industry, hence it is not difficult to apply.

5.4.3 Implications for Practitioners

Health issues are under-represented in the safety literature compared to accidents, hence there is a need to develop an instrument to manage both health and safety. It is much easier for industry people to manage safety because an accident tends to have immediate consequences. By contrast, health problems are difficult to identify in the workplace, and some of the health problems require a period to occur or cumulative exposure. The DQL instrument presented here is focused on hazards and their biological consequences in the manufacturing industry. For its implementation, the methodology requires input from a number of industry professionals, such as an engineering technologist, H&S, and occupational hygienist/therapist. In principle, the methodology is applicable to other areas, such as construction, chemical and process engineering, agriculture, etc.

5.4.4 Limitations of the Work

The work has a number of limitations. One of these is the need for frequency and likelihood data, which is subjective. This is, similar to the subjective estimates needed for consequence and likelihood in the conventional risk assessment method. A second limitation is that we have used representative data to evaluate WHODAS scores. It could be interesting to see the variability between workers (and possibly across different cultures) to the WHODAS scores. A third limitation is that loops of causality have not been included in the work. Some factors (such as lighting and noise) cause fatigue, which may reduce concentration and increase the risk of accidents. A fourth limitation is that determination of an unacceptable threshold for the DQL score was set at >1, but this was our subjective evaluation. It is difficult to see how this score might be objectively determined.

The work was developed with industrial workers in mind, specifically manufacturing engineering. How well the method might apply to other areas has not been determined. Since the WHODAS is a not a sector-specific measure, it is possible that the DQL may be applicable more widely, but this would need to be verified.

5.4.5 Implications for Further Research

WHODAS scores for different stakeholders could be identified. This could involve developing a survey wherein respondents record the impact on their quality of life for each of the biological consequences identified. It may be necessary to simplify the list of biological consequences to avoid survey fatigue. It would be interesting to see if different groups, e.g., categorized by experience, appraised the consequences differently. A statistical approach may be useful here. A possible concurrent project could be to use qualitative research methods to determine why people made the responses they did. This might involve semi-structured interviews or semantic analysis. The DQL method could also be applied to other industries, such as construction.

Additionally, methodologies for control consequences at work need to be improved, especially in health aspects. Some potential barriers could be, for example, sound isolation (noise), ergonomics work station (manual work activity), and good quality PPE (chemical exposure). Hence, a potential research on efficient treatments for controlling health consequences at work may be valuable. However, some health consequences arise not only from the workplace, but rather individuals' lifestyle choices (exercise, diet) and existing health conditions that occur outside of their workplace. Mental health needs to be considered as part of risk assessment too. Thus, we suggest there may be other potentially fruitful research to be undertaken on developing methods to provide a more holistic assessment of worker well-being.

5.5 Chapter Conclusions

We have developed a methodology to measure occupational health harm in the workplace. The principles are based on identifying the likelihood of an exposure, and evaluation of the biological consequences using the WHODAS 12-item inventory. This results in an overall metric of risk for the activity, which is called the Diminished Quality of Life score. This may then be included in risk prevention treatments. In this way, a method has been devised to evaluate long-latency harm, cumulative effects, and chronic injuries.

Chapter 6: Plant System Simulation for Engineering Training Workshops

This chapter contributes to the following publication:

Ji, Z., Pons, D., and Pearse, J., Plant system simulation for engineering training workshops. *Computer Application in Engineering Education*. 2019; 1–14. https://doi.org/10.1002/cae.22171

6.1 Chapter Introduction

Plant (PSE) is a method of efficiently integrating machinery and human labour. Studies in PSE have been mainly concerned with production facilities rather than teaching facilities. Conventional simulation methods assume the *product* moves through the workstations. In the more complex situation of the training workshop, both the student and the artefact being produced move through the workstations. Hence a training workshop requires a fundamentally different way of approaching the simulation. Also the waiting time experience of the students' needs consideration, from a teaching perspective. We adapted the system simulation methodology by including multiple work-streams through the workshop, and by adding decision stages into the model. The method was applied to a training workshop. The results identified specific changes in the way the students were assigned to machines, and the number of different types of machines, that would improve the operation of the facility. The improvement measures were reduction in waiting time by students, and greater machine utilisation. Multiple different class sizes were explored. The approach is broadly applicable to other situations where the people move through a facility along with a partially completed physical product. This work develops an approach to optimise the performance of a manufacturing system, for the unusual class situations where the product moving through the simulation is not merely a physical product as in conventional simulation approaches, but rather the combination of people (students) and their partially completed physical product.

6.2 Approach

6.2.1 Purpose

The purpose of this research was to adapt plant systems simulation to optimise engineering training workshops.

6.2.2 Methodology

The approach was for the first author to attend the course and become familiar with the work flow. This provided the contextual knowledge for development of a simulation model. The software used was Arena (version 15.1) [141]. Quantitative data were obtained from an expert, namely the workshop supervisor. These data comprised minimum, expected, and maximum times for each task.

The next challenge was to find a satisfactory solution. In this case satisfaction is defined as a solution that minimises time waste (waiting time of students), and optimises machine utilisations. These are conflicting requirements, hence a balance is needed. In this research, we define the optimising loops as *identify problems*, *develop solutions*, *test solutions*, *analyse the results,* and finally *adopt the positive solutions*.

Subsequently, optimising cases with different manufacturing attributes were designed. Attribute changes consisted of adding resources, removing resources, and changing the workflow. Optimising cases were then programmed in the simulation and analysed. Finally, the results of different optimised plans were compared, and a satisfactory solution was summarised. This methodology is shown in Figure 6.1.

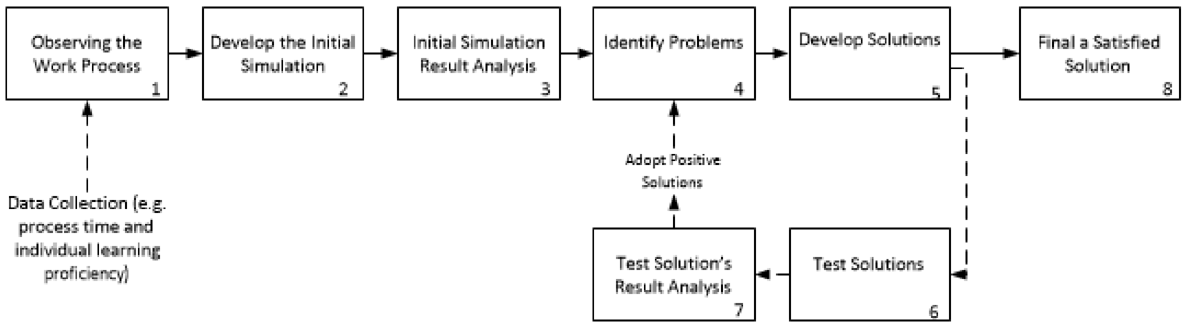

Figure 6.1: Methodology for plant system simulation

6.2.3 Research assumptions

The optimisation had several objectives. The first aim was decreasing students' waiting time in each activity, for example waiting for available machines. Another aim was to increase the machinery utilisation.

Simulations assumptions were:

1. Hand tools (such as manual hacksaw and files) are available in large numbers.
2. No machine is unavailable (no breakdowns).
3. Set up time for each activity is fixed.
4. Students arrive on time; all students are present for each session.
5. Student travel time between stations is neglected.
6. Students transfer safely between machines and materials, and machines are not operating while student are transferring between machines.
7. Students follow instructions.
8. Supervisors are experienced and always available for help.
9. No work is redone.

Most of these assumptions are reasonable, but two need elaboration.

Of the above assumptions the most restrictive might appear to be 'no breakdowns'. However experience shows that the machines have a high reliability, and this is because the workshop is not continuously used, and the sessions are of comparatively short duration (about 4 hrs). Hence, while machines do require maintenance, this may generally be conducted between the teaching sessions.

Another potentially restrictive assumption is 'Supervisors are experienced and always available for help'. In our case, students work at their own paces, and also they are doing this training course for the first time. For safety and training purposes, students are only allowed to continue to the next step after a supervisor check. This situation may potentially result in long waiting times if the supervisor is busy elsewhere. In our case there are two tutors so the issue seldom arises, and we have not included it in the model. We mention this in case others seek to apply our method to slightly different situations.

6.3 Results: Case Simulation

6.3.1 Background information of the workshop

The workshop teaches students the basic workshop processes within 36 hours. Multiple type of the machines are available in the workshop: 6 lathe machines, 4 milling machines, 2 drilling machines and a large number of manual hacksaw and files. The manual tools are set as 4 handcraft stations. Both machines and manual tools are in good quality and available for students to use. The workshop runs 21 classes per year with up to 10 students in each class.

The project undertaken by students is to make a tap wrench. This has five parts: two handles, two jaws and a body. Students mainly use a lathe and mill, see Figure 6.2.

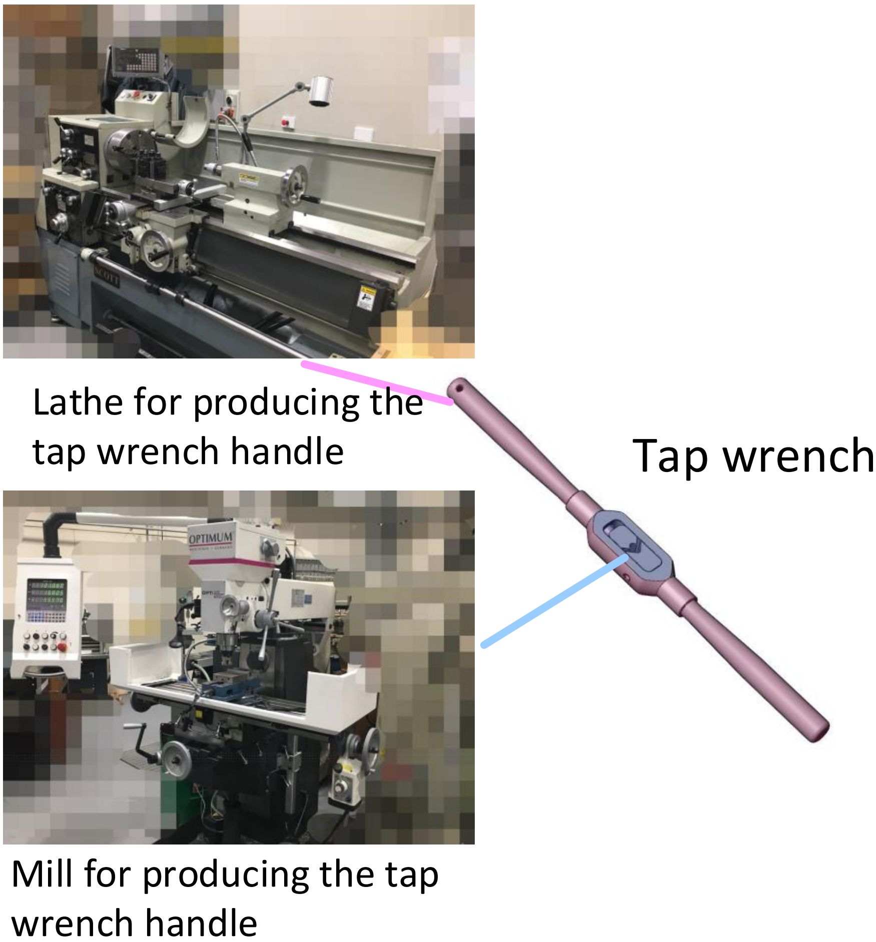

Figure 6.2: Tap wrench components and associated machine

All students work individually, but in a shared workshop where there are insufficient machines for dedicated continuous use. Additionally, students are not prescribed the manufacturing process steps – instead they are expected to do their own thinking about cutting sequences and then check these with the tutor for feasibility and safety. There are limited numbers of machines and consequently students share machines (turn taking), and may have to wait until machines are free. This situation is very different from conventional production plants and imposes challenges for simulation.

The two main production routes are to start with either the parts requiring turning or milling. Given that there are a total of 10 machines (six lathes and four mills), and 10 students, all students are occupied initially. Students (10 students average in one course, minimum 9 and maximum 11) are divided into two groups. Initially Group 1 uses the lathes to work on the handle while Group 2 uses the mills to work on the body. After finishing the first process of their work, Group 1 follows a work sequence comprising jaws, body, polishing and assembly. Group 2 follows the work sequence of jaws, handle, polishing and assembly.

The situation is complex and unpredictable because students work at different individual paces. Also, they are doing a task for the first time, hence have different levels of underpinning familiarization with machining technology or the principles thereof. Each student is on individual pedagogic journeys of different durations. Thus the duration that a student spends on a machine is variable.

As a consequence a slower student utilises a machine for longer, and this affects other students who need the machine. From a simulation perspective this adds the significant complication that the production flow (layout) is not fixed.

There is also an opportunity for students to do some other training projects when they finish their tap wrench work in 36 hours, the extra project (welding training or harmer machinery) is not mandatory. However, this is not an assessed part of the course, and is excluded from the subsequent simulation. Nonetheless the plant simulation can perhaps find ways to make it more likely that students would have sufficient free time, in coherent blocks of time, to undertake these additional learning experiences.

6.3.2 Collection of data

The course under examination has a duration of 36 hours. A high level categorisation of the time allocation is shown in Figure 6.3. Approximately 20 hours (of the total available time) are spent on machine operations to manufacture the tap wrench.

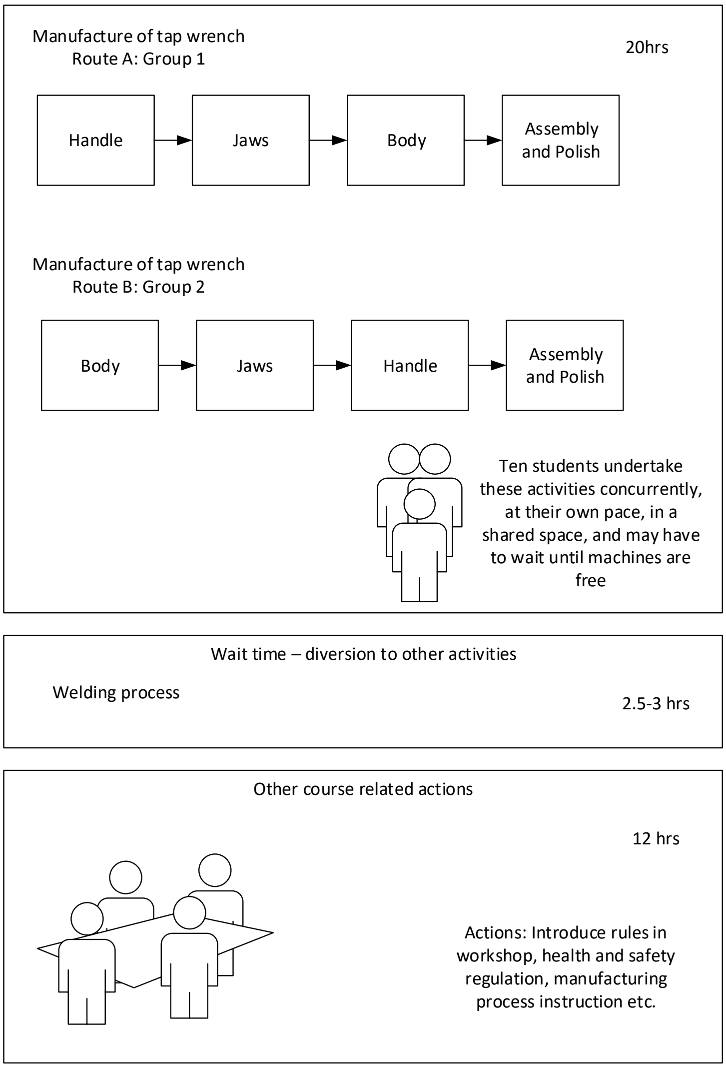

Figure 6.3: Observed time utilisation

The technician in charge has trained hundreds of students, and estimated the typical times for each operation based on his experience of how long students of different ability take, see Table 6.1.

No. Process	Process Part	Process Name	Resource	Process Time Duration (Minutes: Minimum, Average, and Maximum)		
1	Handle	Turning Handle	Lathe Machine	40	60	80
2		Cutting Handle	Lathe Machine	4	10	15
3		Thread Handle	Handcraft	8	15	25
4		Hole Handle	Lathe Machine	5	10	15
5	Jaws	Turning Jaws	Lathe Machine	20	35	45
6		Cutting Jaws	Milling Machine	15	25	45
7		Finish Jaws	Milling Machine	30	40	45
8		Square Jaws	Milling Machine	7	14	21
9		Filling Jaws	Handcraft	15	25	60
10	Body	Shape Body	Milling Machine	30	45	60
11		Hole Body	Drilling Machine	30	40	50
12		Slot Body	Milling Machine	90	180	270
13		Thread Body	Handcraft	15	20	30
14	Assemble and Polish	Assemble	Handcraft	10	15	20
15		Polishing	Handcraft	60	90	150
Other Information	Welding	2.5-3 hours				
	Total Time	36 hours				

Table 6.1: Estimated time for each activity

6.3.3 Simulation results

Simulations were designed for different scenarios, see Table 6.2. The scenarios were created to explore whether additional equipment could improve the student experience and productivity of the facility.

Scenario Name	Status	Description
Scenario A	Status quo	Students are divided into two groups (Group 1 and 2). Group 1: follows the sequence making handle, jaws, main body and assembly. Group 2: follows the sequence main body, jaws, handle, and assembly. Both group have to finish handle, main body and jaws to complete the task.
Scenario B	Keep students divided into two groups, at least initially.	Group 1: After completing the handle, students then choose making jaws or main body and joining the shortest waiting line.

		Group 2: After completing the main body, students are allowed to choose making jaws and handle by themselves, but join the shortest waiting line.
Scenario C	Same as Scenario B, but add one milling machine.	Same process sequence description with Scenario B
Scenario D	Same as Scenario B, but add one milling machine, and remove a lathe.	Same process sequence description with Scenario B
Scenario E	Same as Scenario B, but add one milling machine, and remove two lathe.	Same process sequence description with Scenario B
Scenario F	Same as Scenario B, but add one milling machine, and remove three lathe.	Same process sequence description with Scenario B
Scenario G	Same as Scenario B, but add two milling machine.	Same process sequence description with Scenario B
Scenario H	Same as Scenario B, but add two milling machine, and remove one lathe.	Same process sequence description with Scenario B
Scenario I	Same as Scenario B, but add two milling machine, and remove two lathe.	Same process sequence description with Scenario B
Scenario J	Same as Scenario B, but add two milling machine, and remove three lathe.	Same process sequence description with Scenario B
Scenario K	Same as Scenario B, but add three milling machine	Same process sequence description with Scenario B
Scenario L	Same as Scenario B, but add four milling machine	Same process sequence description with Scenario B

Table 6.2: Simulation scenario description

Result: Scenario A - Status quo

Under the existing workflow sequence the ten students are divided into two groups (Group 1 and Group 2). Due to the number of machines (six lathes, and four mills), supervisors usually let six students make handles (using lathes), and the other students make the body (using mills). Then, Group 1 follows the work sequences by handle, jaws, body, polishing and assembly. Group 2 follows the work sequences by body, handle, jaws, assembly and polishing work. For safety, students must check with the supervisor before they start to do any new activities. The layout of the work process is addressed in Figure 6.4; time cost results are shown in Table 6.3; machine utilisations are shown in Table 6.4; and the simulation program is shown in Appendix C.

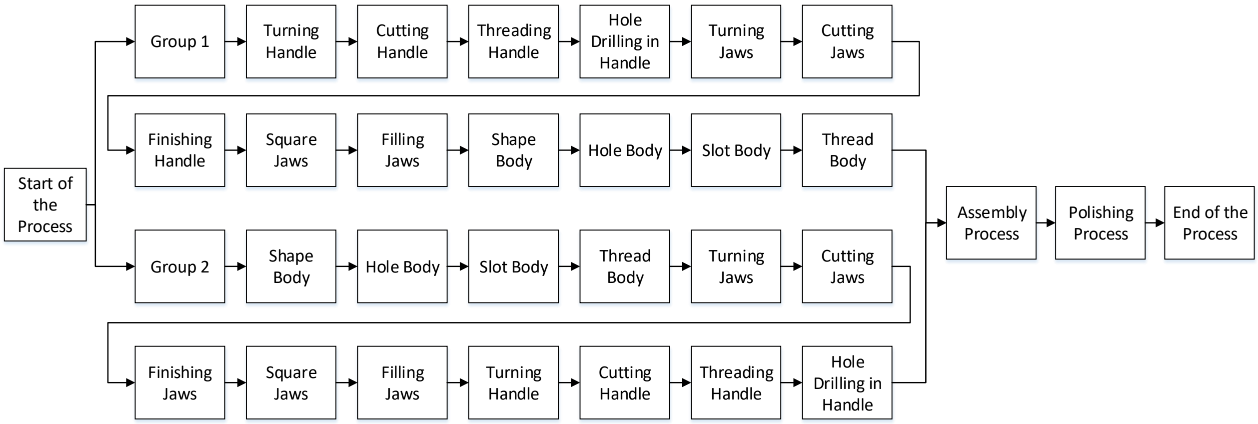

Figure 6.4: Scenario A- Simulation Programme

Result Categories	Average Time	Minimum Average Time	Maximum Average Time	Minimum Value	Maximum Value
Value Adding Time	644.97	608.92	692.84	521.36	792.08
Wait Time	238.72	204.32	273.65	38.12	528.98
Total Time	883.69	813.25	947.94	598.99	1217.37

Table 6.3: Scenario A- Time Cost Result (Unit: minutes, Student number: 10, Replication Time: 200)

Machine Station Type	Minimum Average Utilisation	Average Utilisation	Maximum Average Utilisation
Drilling Machine	16%	18%	22%
Milling Machine	62%	67%	72%
Lathe Machine	15%	17%	21%
Hand Tool Station	16%	18%	20%

Table 6.4: Scenario A- Machine Utilisation (Student number: 10, Replication Time: 200)

The simulation results show that students take 883.69 minutes on average for this process. This includes the time spent on learning how to operate machines, read drawings, and also to understand the safety work procedures. The waiting time in Scenario A is 238.72 minutes on average, which means 27% of the total time was wasted in waiting; we propose that this is not a satisfactory outcome and needs to be optimised in the further simulation (See Scenario B). Utilisation of the milling machine was 62% on average, which is a high rate and also means that most students were using milling machine in their work. We propose that this may be one of the reasons for the long average waiting time (AWT).

Result: Scenario B

In Scenario B, the students join the shortest waiting line. This is based on the limitation of the number of machines (six lathes and four mills). For example, if students choose to make a handle first, they then need to go to whichever is the shorter waiting line between body process and jaws process. The waiting line of body and jaws are dependent on the available number of mills and lathes. After students finish all three parts, they may proceed to assembly and polishing. The challenging feature of this simulation is the need to model the change in workflow. This was achieved by including adding attributes to each student in the model, and to represent the states of the various tasks. Then a decision module was added to the programme to direct each simulated student to the appropriate workflow. In contrast a conventional plant simulation only tracks the progress of a product through workstations, whereas here the product comprises students and the parts they have completed as well as how those interact with the workstations. The workflow of Scenario B is shown in Figure 6.5; time cost results are shown in Table 6.5; machine utilisations are shown in Table 6.6; and the simulation program is presented in Appendix C.

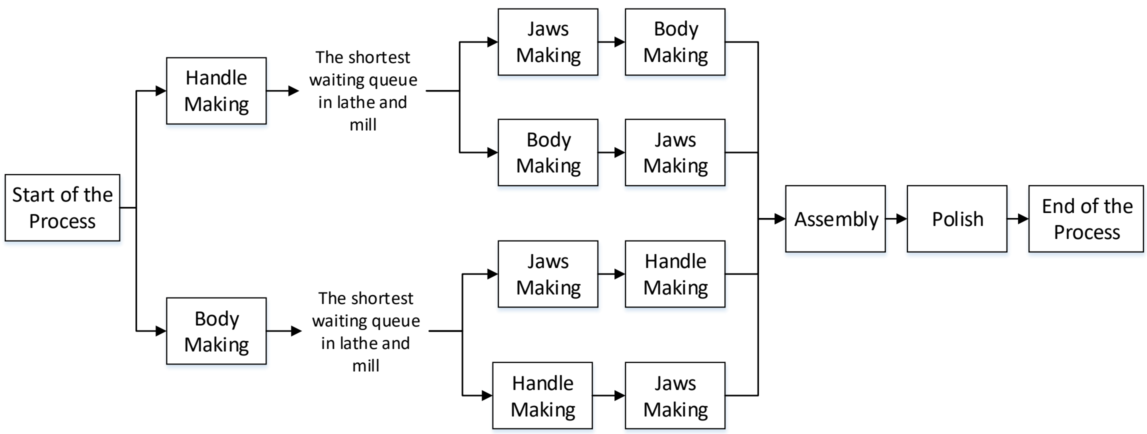

Figure 6.5: Process Workflow for Flexible Method

Result Categories	Average Time	Minimum Average Time	Maximum Average Time	Minimum Value	Maximum Value
Value Adding Time	712.67	669.56	750.07	522.34	917.38
Wait Time	210.89	169.10	246.78	36.16	462.05
Total Time	923.57	854.82	974.47	601.97	1257.32

Table 6.5: Scenario B- Time Cost Result (Unit: minutes, Student number: 10, Replication Time: 200)

Machine Station Type	Minimum Average Utilisation	Average Utilisation	Maximum Average Utilisation
Drilling Machine	16%	18%	20%
Milling Machine	62%	67%	71%
Lathe Machine	22%	23%	28%
Hand Tool Station	15%	18%	20%

Table 6.6: Scenario B- Machine Utilisation (Student number: 10, Replication Time: 200)

We found that the average waiting time in Scenario B was 210.89 mins, and this is 12% less than Scenario A. Scenario B has the same result as Scenario A in terms of mill utilisation (62%), hence we propose that this is still not a satisfactory result. Therefore, we continued working on the simulation, and proposed some other optimisation scenarios (see Section 4.3.3).

Comparing Scenario A and Scenario B, we found that Scenario B provided less waiting time. However, we found that the utilisation of milling process in both Scenarios A and B is much higher than other machines. This means milling machines are dominate the overall process and students spent most of their activity and time in the milling process. Hence a potential method to optimize the system is to employ more milling machines and reduce the number of lathes or drills. We also found that there was less time and fewer activities spent in the drilling process. Hence we identified these as low priority for optimisation. Drills are also less expensive machines than lathes or mills, and take up less floor space.

Therefore we added or removed resources (mill and/or lathe). We then evaluated the result and determined the best machine arrangement for the system (for arrangement details, see Figure 6.5).

4.3.3 Result: Scenario C, D, E, F, G, H, I, J, K, and L

Scenarios of C, D, E, F, G, H, I, J, K and L were designed to represent several arrangements. We ran every scenario simulation with 200 replications. The average waiting times were analysed, results shown in Figure 6.6.

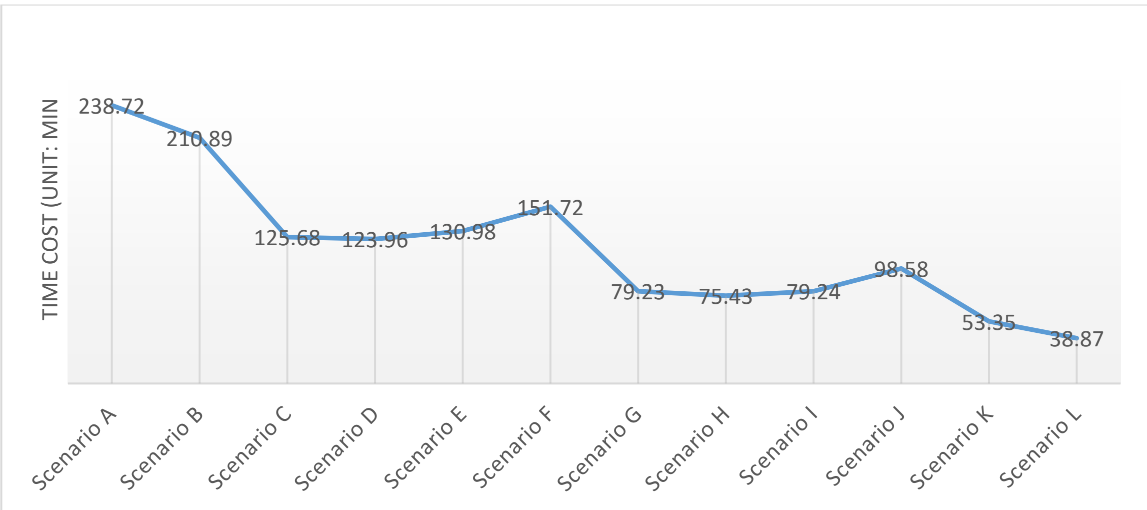

Figure 6.6: Average wait time (Time unit: min)

Determine Lathe Machine Arrangement

We found that removing one lathe from the system does not affect the waiting time much, but has a slight upward trend in the waiting time when two lathe were removed (Scenario E to Scenario F, and Scenario I to Scenario J). But when three lathes were removed, there was a significant increase in the waiting time. We then analysed the lathe utilization, see Figure 6.7. There was a significant increase of lathe utilisation when two more lathes were removed. Hence, combined with the lathe utilisation and the waiting time, we propose that removing two lathes is the best solution.

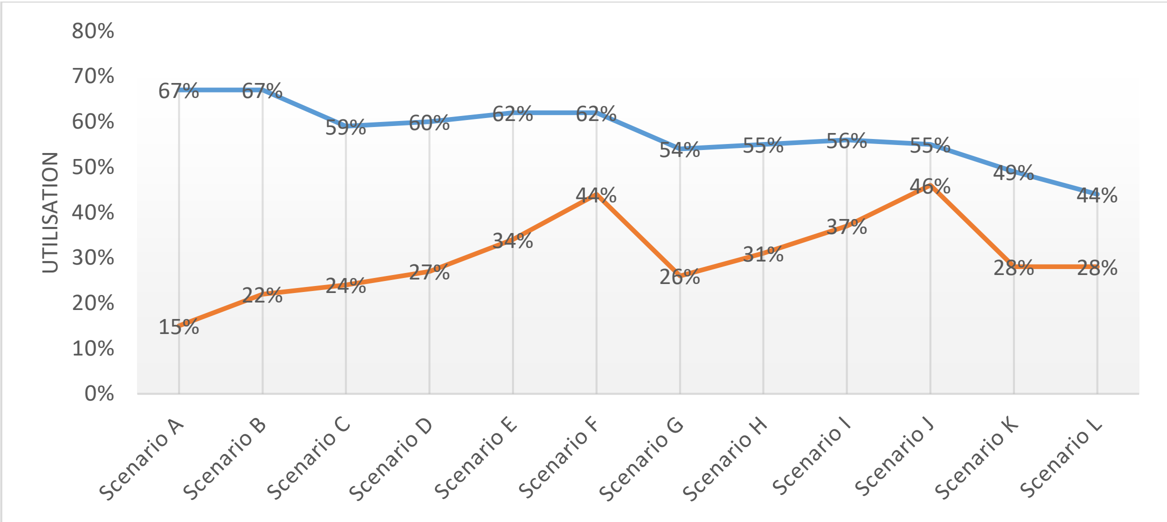

Figure 6.7: Average utilisation of mill and lathe (Blue: mill; Orange: lathe)

Determine Milling Machine Arrangement

Adding mills can significantly reduce the waiting time, see Figure 6.8, (Scenario C, Scenario G, Scenario K and Scenario L). We also found that the waiting time reduction by adding milling machines was not linear, see Figure 6.14. The most waiting time reduction was achieved in Scenario C. This was achieved by adding one mill and saving 85.21 mins.

Hence, combining both potential solutions in lathe and mill arrangement, we propose that Scenario E (add one mill and remove two lathes) and Scenario I (add two mills and remove two lathes) are the best of the arrangements.

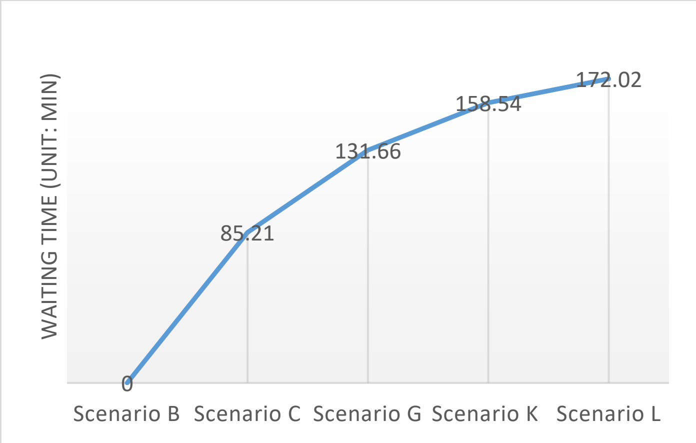

Figure 6.8: Average Reduced Waiting Time (Time Unit: Min)

4.3.4 Result: Analysis of different input in number of entities

The workshop takes 10 students on average, but occasionally more (13 students) or fewer (8 students). Hence, in considering the best arrangement of machines, we should also consider the situation with different numbers of students. We then reset the entity number in Scenario E and Scenario I simulations. The resulting waiting time costs are shown in Figure 6.9.

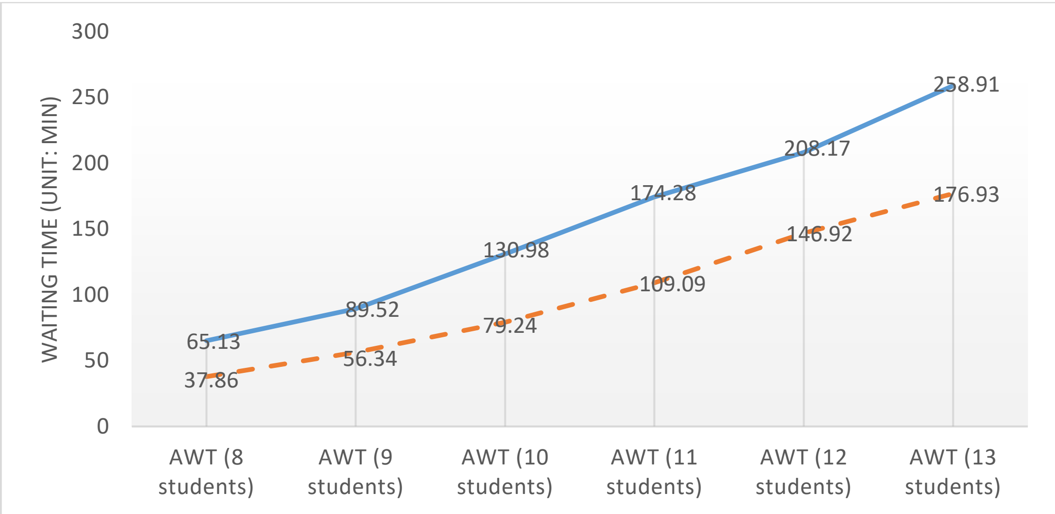

Figure 6.9: AWT Cost in Different Number of Student (Solid: Scenario E, Dashed: Scenario I)

We found that the machine arrangement of Scenario I shows a better performance than Scenario E in the overall waiting time. The waiting time of Scenario E was at a reasonable level with 8 and 9 students, but it then rose to 130.98 mins when 10 students joined in the system, and reached 258.91 mins when there were 13 students. By contrast, the waiting time cost trend in Scenario I shows a steady increase from 8 students to 13 students. This is because Scenario I has one more milling machine, and it increases the overall capability of the system when processing more students.

6.4 Chapter Discussion

6.4.1 Summary

This paper applied a system simulation methodology to enhance the productivity in a training workshop. We identified benefits from a specific change in the number of machines (Scenario I). It involves dividing the students into two initial groups that go to either the lathes or mills, and thereafter join the shortest waiting line for the next task. This scenario has a hardware complement of four lathes (two less than the status quo) and six mills (two more than the status quo). It has several advantages as follow. First, it has a reasonable machine utilisation in lathe, mill, drill and handcraft. Second, it significantly reduces the average waiting time compared to the original plan, which allows the supervisor to spend more time in teaching, or introducing more operation activities, such as welding. This also allows students to spend more time on one specific activity. Third, Scenario I has a reasonable capacity when dealing with fewer or more student numbers.

Alternatively, this methodology has a special focused on reducing students' waiting time. We conclude this may bring multiple benefits. It enhances the individual experience, both for students' learning experience and staff working experience. For students, less waiting time may increase their satisfactory while engaging the courses. It may also assist for mastery of the topic. Less waiting time also allows student to spend more on their value adding learning, such as the optional welding and other projects.

For staff, less student waiting time can potentially reduce their workloads and decrease their work pressure during supervision, hence can potentially increasing their teaching quality.

Another benefit is for safety outcomes. Less waiting time reduces the performance pressure on students: it reduces the risk of being hasty merely because there is a queue of other students needing to use the machine. Moreover, waiting time reduction also decreases the chance of boredom accidents.

There is also a benefit in economic outcomes. There is an opportunity to increase the university Equivalent Full-Time (EFT) capabilities, which allows the workshop to process more students at one time. Additionally, it also provides the basis to make rational decisions on the balance between investing in staff and equipment.

These benefits are summarised in Figure 6.10.

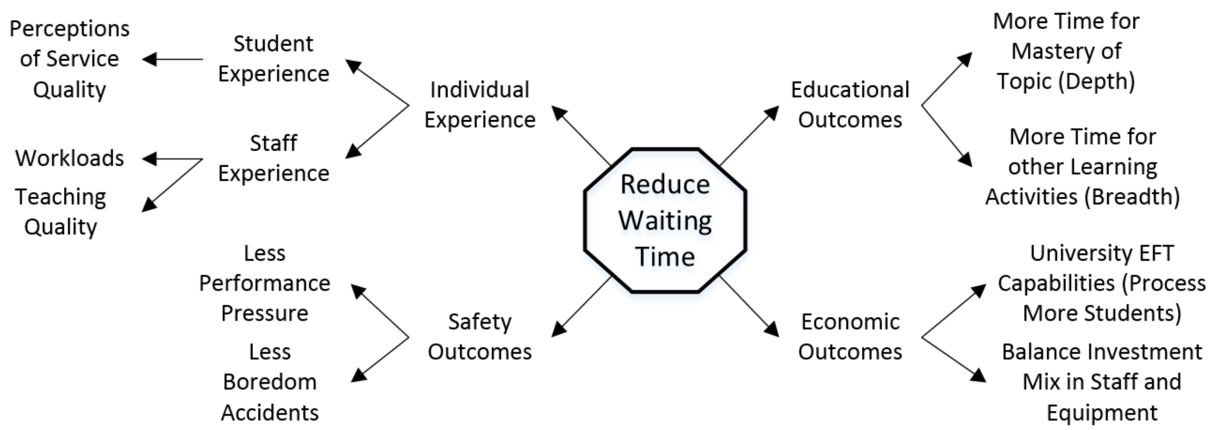

Figure 6.10 Benefits of reduced waiting time

6.4.2 Original contributions

This work develops an approach to optimise the performance of a manufacturing system for the particular situation where the product moving through the simulation is not merely a physical product as in conventional simulation approaches, but rather the combination of people (students) and their partially completed physical product. This is an unusual class of simulation, and we have shown how it may be approached by including additional attributes and decision stages into the model.

Another novelty of the work is the application to a training workshop in an educational context. The methodology we explored has a focus on saving students' waiting time. This gives more time for students to learn on other voluntary activities including welding, or making an additional item of a tap hammer. Moreover, waiting means people doing nothing, and this can result in boredom accidents, and become a safety hazard.

6.4.3 Limitations of the work

The primary limitation is that the analysis, while based on accurate input data, has not been validated by applying the intervention. We have piloted a method to design teaching facilities to reduce the waiting time experienced by students, but have not implemented the recommended hardware changes. Hardware changes would be needed to verify the time gains. It would also be useful to measure the improvement in educational outcomes or satisfaction for students.

A significant limitation is that the optimisation is based on an assumption that the specific product (tap wrench) continues to be made. If the workshop was instead to be used to manufacture another product, or multiple different products, then the conclusions of the simulation will no longer be valid. Nonetheless we expect that the method developed here should be applicable. An extreme situation may be envisaged where each student was doing his/her own individually motivated project, i.e. a type of one-of-a-kind manufacturing process. Such situations are challenging from any simulation perspective.

Another limitation was the subjective nature of the time estimates. These relied on the opinion of an expert tutor. For greater accuracy it would be necessary to obtain quantitative data by measuring student durations. Furthermore, the time estimates were based on 10 students in a course. This workshop course runs many times a year, and there are partial day, partial night, and full day occurrences, which correspond to a type of shift situation. The activity times may be different in different shifts.

6.4.4 Implications for further research

A possible direction for future research could be to link economic parameters with the arrangement optimisation, for example different costs of machines, materials, and supervision. Another could focus on the educational outcomes, perhaps by correlating the activity times with individuals' learning proficiency and learning curve. Developing ways of simulating one-of-a-kind situations is another potentially useful line of research.

6.5 Chapter Conclusions

Conventional simulation methods assume the product moves through the workstations. In the more complex situation of the training workshop, both the student and the artefact being produced move through the workstations. We developed an adaptation of the system simulation methodology for this situation. This was achieved by including additional attributes and decision stages into the model. The method was applied to a training workshop. The results identified specific changes in the way the students were assigned to machines and the number of different types of machines that would improve the operation of the facility. The improvement measures were reduction in waiting time by students, and greater machine utilisation. Multiple different class sizes were explored. The approach is broadly applicable to other situations where the people move through a facility along with a partially completed physical product.

Chapter 7: Integrating Occupational Health and Safety into Plant Simulation

7.1 Chapter Introduction

Managing occupational health and safety (H&S) risk has become increasingly the important for modern workplaces [2, 318]. Existing methodologies are primarily focused on reducing consequences of harm and the likelihood of the occurrence [173]. These risk assessment methods tend to focus on accidents and their immediate consequences [319]. While long term health effects are not precluded, it is often problematic to include them because of the difficulty of prediction [4, 5]. Plant layout and production optimisation are achieved via plant simulation method. These simulations focus on the productivity and time dimension, and invariably ignore the H&S risk. Hence existing methods for plant layout do not provide a means to consider productivity and H&S holistically. This paper develops a methodology to integrate H&S risk into plant simulation. It achieves this using the metric of DQL [2]. The method consequently accommodates long term (chronic) health measures. The specific area under examination is manufacturing industry, although it may well find application in other industries. We refer to this methodology as plant safety simulation (PSS).

7.2 The Interrelationship between Plant Simulation and Plant Safety

Plant simulation is a method of modelling the movement of people and products through production facilities. It uses Monte Carlo methods to model variable time durations of specific processes [320]. It originated in production engineering [321-323] and has extensive applications [7, 184, 324]. It has been used to achieve increased productivity by avoiding waste or decreasing cost [156]. It forms the basis for many other applications where a process is simulated, such as in plant construction [324], and chemical plants [325]. Basic plant simulation uses continuous variables and probability distributions, whereas more complex models are based on discrete event simulation (DES) [326]. Plant simulations are manifested in software such as Arena [164], Witness [327], or Tecnomatix [328, 329].

The literature relating to simulation *application* is large. In contrast the literature on new developments in the plant simulation *methodology* is relative sparse. The main developments over the years have been to strengthen the discrete event simulation component [330, 331], addition of analytical hierarchy process (AHP) [332], inclusion of fuzzy methods [333], and incorporation of multi-criterion decision-making (MCDM) [334, 335].

The primary purpose of plant simulation is to model the production economics, in terms of time taken, plant utilisation, productivity, etc. However for all production plants there is another dimension to consider, which is the safety of the workers. Previous plant simulation research has been mainly focused on the plant economics rather than H&S.

The historical focus of H&S risk has been about reducing harm to workers in high risk industries, and by the mid 1800's there arose in Europe a degree of legal protection for workers in designated industries such as factories and mines [336]. Later in the 1900's that expanded to other areas such as agriculture. General H&S legislation arose in the 1970s, and marked a shift from detailed legislation for specific situations, to general frameworks and systems. This subsequently led to the concept of risk being the combination of consequence and likelihood as embodied for example in AS/NZS 4801:2001 [21] and ISO 31000 [4]. Thus, the focus of H&S became one of reducing accident occurrence and minimising harm, by avoidance or providing protection [319]. Many countries developed regulations to manage risk at work H&S [64, 337]. A large body of research has arisen, some notable biological consequence are associated with amputation [276], hearing loss [270], and musculoskeletal disorders [338].

A more recent development, and a particularly difficult problem in the area of H&S analysis, is predicting the long-term health risks. The safety component, which largely refers to the immediate consequences of identifiable accidents, is relatively well captured by the risk assessment methodology [43]. However, the long term harm is more problematic because the initiating incidents may be difficult to identify, small exposures may be cumulative, and the harm may only appear later in life, and hence difficult to associate with a particular industry practice or task [1]. Legislation is beginning to create an expectation that organisations manage the long term risks of harm for their workers, but there are few if any supporting methodologies [338].

Our previous attempts to address this included the development of a methodology for assessing H&S risks for specific manufacturing tasks, hence the concept of DQL [2]. The DQL methodology is based on identifying the frequency of an incident and likelihood of exposure, and then scoring health consequences. This results in an overall metric for H&S risk for an activity. DQL was developed as an extension of an existing instrument measuring the quality of life, namely WHODAS [114]. However there is little integration between the literature on plant simulation, and industrial safety. The two are commonly treated as independent activities, which is odd given that human operators are common to both.

There have been many applications of modelling of safety outcomes. For example real time and mathematical models have previously been applied to estimate industry accidents [184]. Decision making relating to safety actions and team training have been developed based on Immersive Virtual Environments [185]. Computer based simulation methodologies were also applied to safety training [186]. Explicit representation of plant operation was identified for managing complex working process [187]. The relationship between person-related factors (e.g. risky-decision making, control beliefs, and general mental abilities) and their probability of violation in a production context were investigated, using factorial experimental design methodology [188].

However there is currently no methodology which incorporates the safety risk considerations as well as plant simulations.

7.3 Research Approach

7.3.1 Research Preamble

An approach is sought to integrate OHS risk with plant simulation in the context of manufacturing industries. Prior work has shown the development of the DQL concept, which is primarily designed around an established and validated medical and rehabilitation definition of quality of life, which in turn is based on the extent to which people may be unable to undertake tasks in daily life, e.g. getting dressed, joining in community activities, and maintaining friendships. The novel part of the DQL idea was to apply this instrument to determine the reduction in quality of life that might be caused by present work activities [2]. In this way, the method accommodates chronic, cumulative, and long-term health consequences. This provides the means to better include health in the safety risk assessment processes.

However, previous work did not provide an integration with plant simulation, which is the purpose of the current work. The challenges to achieving this were that plant simulation is not designed for calculating such risks. The approach to overcome this was to create additional sub-modules or 'routines' to perform the calculations. Another challenge is that ideally the plant simulation would include a database such that both the production economics and health attributes of an activity could be managed together, however this is not a feature of the current generation of plant simulation software. Consequently, the present approach was to manage the health attributes independently.

The resulting methodology provides a proof of concept for the integration of plant simulation and H&S assessment. We refer to this methodology as PSS.

7.3.2 Methodology

The process adopted is illustrated in Figure 7.1. The starting concept was that the operations management, via the workflow and schedule, results in mobilisation of human and machine resources, which in turn results in the exposure to various types of harm. The first step in developing a method of modelling this was to determine a suitable safety risk methodology. There are many existing safety risk methodologies; DQL was selected here. A further advantage of the DQL methodology is its inclusion of long-term health issues. The DQL methodology is based on frequency, likelihood, and consequence, and the simulation was adapted to accommodate these variables. The DQL also provides an integration with conventional risk assessment, thereby providing a mechanism to evaluate both the accident and long-term health risks. A method was then developed to integrate this into plant simulation (described below). Finally the PSS method was applied to the specific case of a workshop for different types of machines, e.g. lathe, mill and CNC.

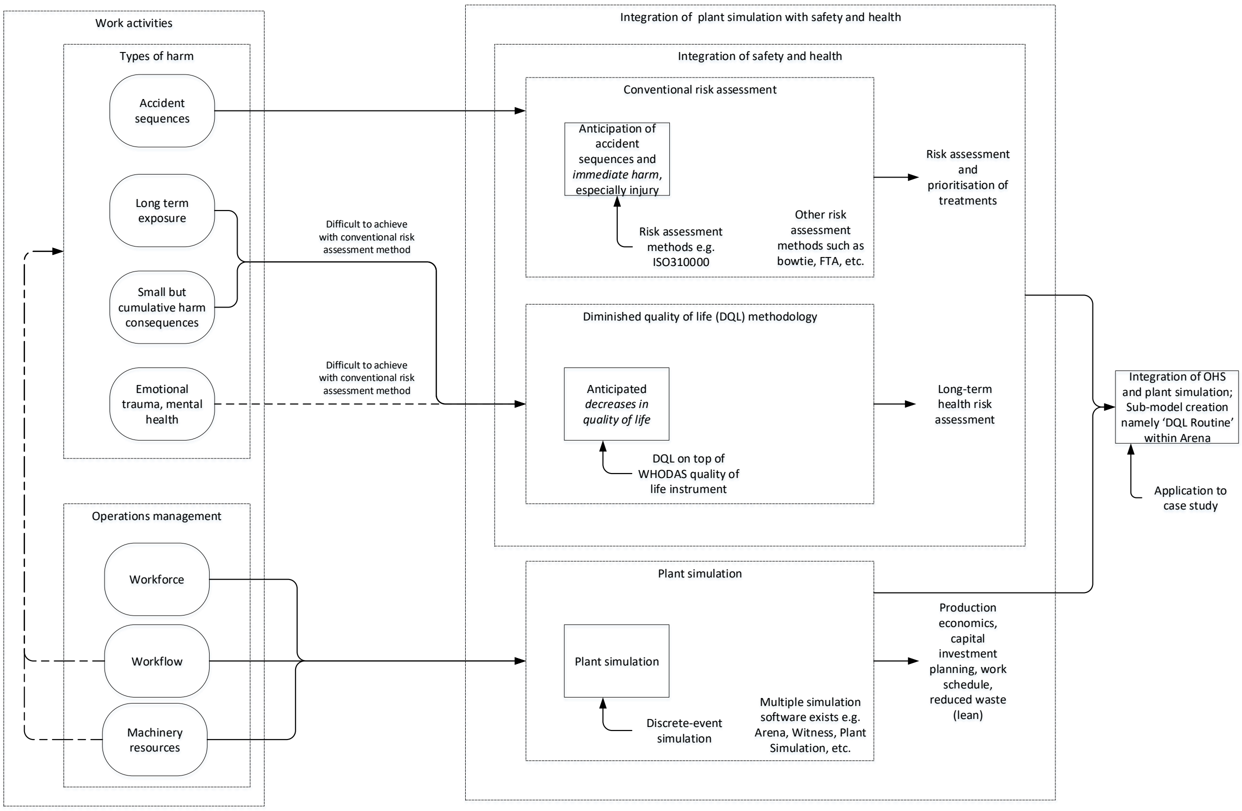

Figure 7.1: Summary of PSS methodological approach, whereby conventional risk assessment was integrated with the health metric (diminished quality of life) and then with plant simulation.

An initial simulation was developed in Arena software (Version 15.0). This software incorporates a *decision model* which provides an efficient way to address the components in DQL, such as frequency and likelihood. DQL methodology was then combined with the workshop system in the simulation. We achieved this by creating, via programming, a *DQL Routine.* This was designed to calculate the safety risk for each part of the incorporated process. These routines are designed using several Arena models, such as *decision model*, *assign model* and *variable calculation model*. We did not include every hazard in the simulation, because DQL contains considerable OHS information, and we were seeking to develop a methodology. Instead, we selected some typical hazards, such as chemical exposure, cutting, crushing and squashing. The process whereby an integration was achieved of the DQL routine and plant simulation is shown in Figure 7.2. The integration achieved here was proof of concept, with the DQL routine being a manual programmed addition. Ideally plant simulation software would enable this type of integration to be handled with less effort, and perhaps this is a potential future development area for software development.

Following integration of DQL into the simulation programme, we built different simulation scenarios to investigate the effects of the different activities on the plant model.

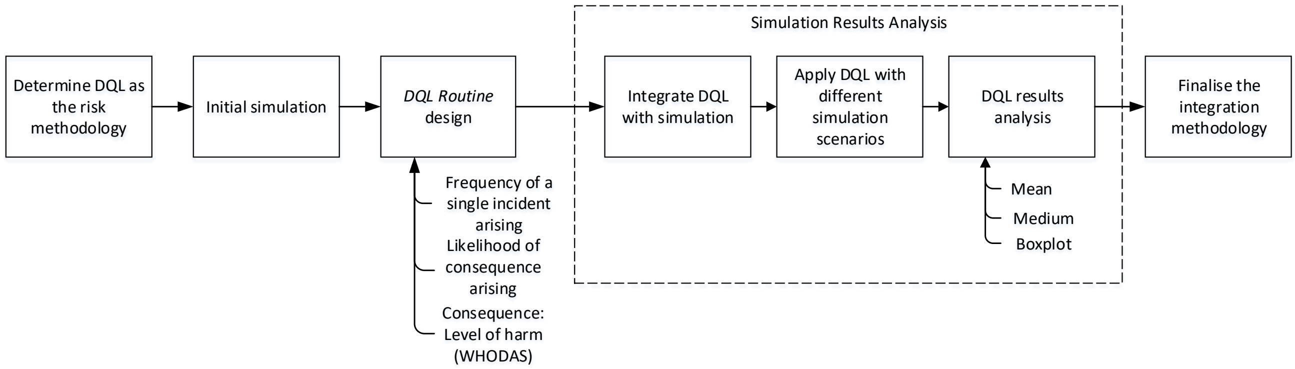

Figure 7.2: Integration of DQL routine and Plant simulation

7.4 Results

7.4.1. Plant simulation model

A case study was conducted addressing the integration of safety risk and plant simulation. The case study was a student training workshop which has the following features:

- The workshop trains students in basic workshop activities in 36 hours.
- Six lathes, four milling machines, two drilling process and a large number of hand tools are available.
- The hand tools are located at ten hand tool stations.
- Both machines and hand tools are of good quality and available.
- The workshop runs 21 classes per year with up to 10 students in each class.
- Machine maintenance is not undertaking during the training period, but is instead done at other times.

The students manufacture a tap wrench from supplied drawings. The tap wrench has five parts (two handles, two jaws and a body). Students work individually, but in a shared workplace where there are insufficient machines for dedicated continuous use. Additionally, students are not prescribed the manufacturing process steps – instead they are expected to do their own thinking about cutting sequences and then check these with the tutor for feasibility and safety. There are limited numbers of machines and consequently students share machines and may have to wait until machines are free to use. Students are also variable in the time taken to complete a task.

The work flow of the training process was identified, see Figure 7.3. The plant simulation model was then built. This was further modified to include the DQL component.

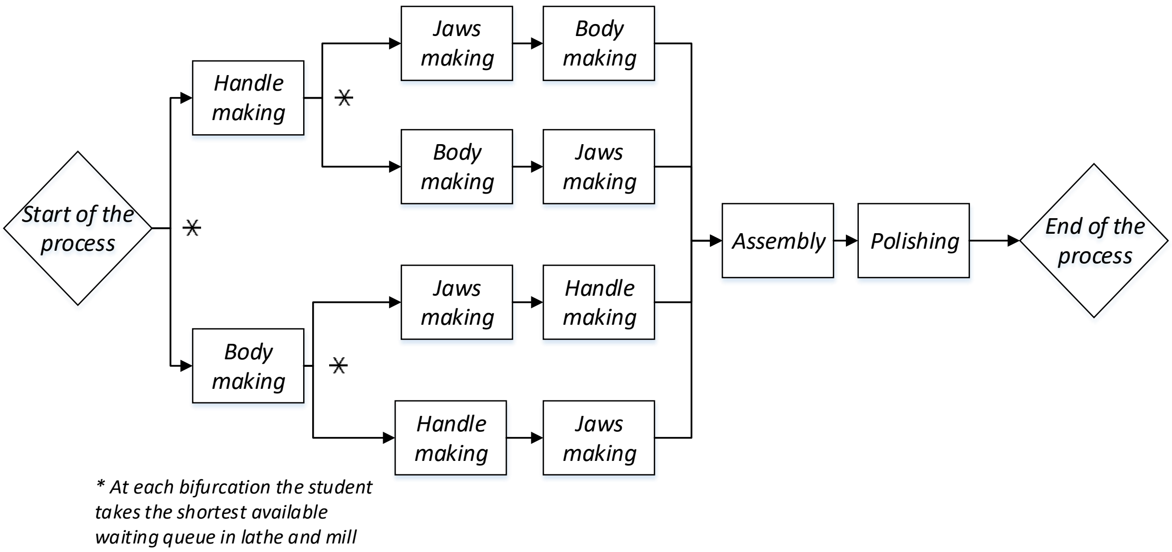

Figure 7.3: Workflow

7.4.2 DQL Routine

The DQL routine is used to determine the diminished quality of life for an activity and for each multiple hazard. The DQL routine incorporates frequency, likelihood, and WHODAS consequence, using the method explained in [2]. This routine may be applied to any activities in the simulation, sometimes with a small degree of customisation. The DQL for each activity is then determined. In parallel the plant simulation is used to determine the production times and efficiencies for that same activity. This DQL routine allows people to visualise the management in H&S.

A simulation representing DQL was developed using Arena. A decision model was used to represent *frequency of an incident arising*, and the *likelihood of exposure.* An assign model was used to locate WHODAS consequence and also calculate the DQL. Additional routines were programmed following different hazards such as *chemical exposure*, *cutting, crushing and squashing*, *dust*, and etc.

The *DQL Routine* was based on three simulation components:

- A *station* model, which was used to connect the DQL routine with the original simulation processes.
- Two *decision* models, which used input data for the *frequency of an incident arising*, and the *likelihood of exposure.* These two components were identified by DQL and determined using probability *percentage* to identify frequency and likelihood. These two DQL components were then programmed by using the decision models. The type of decision model follows the condition *"2-way by chance"*.
- An *assign* model, which was used to record and store the DQL relating to results in the simulation. The assign model was used to achieve two objectives:

(i) Equation (1) was used to count the number of incidents:

$$N_k = N_k + 1 \qquad (1)$$

N: Number of the target incidents arise *k:* The target hazard

(ii) Equation (2) was used to calculate the average DQL score:

$$DQL_{average} = \frac{\sum_{k=1}^{n}(N_{k} \times L_{k})}{N_{E}} \qquad (2)$$

$DQL_{average}$: Average DQL score of the system;

n: Total number of identified hazards;

k: The target hazard;

N: Number of the target incidents arise;

L: Corresponding level of harm;

N_E: Total number of the entities.

The *DQL Routine* provides the user with a virtual representation of the H&S outcome. This allows the most risky activities to be identified in a quantitative way. The risk can be controlled by decreasing the *frequency of an incident arising*, the *likelihood of exposure,* and *level of consequence.* Alternatively, an overall system risk can be determined by using the DQL routine. An extract of "*DQL Routine"* for lathe activities is shown in Figure 7.4.

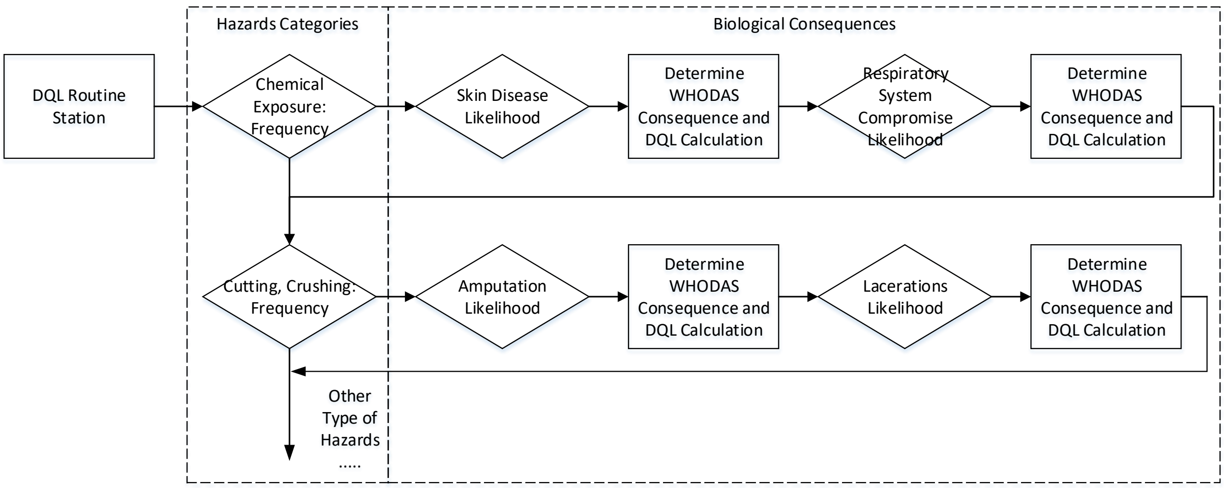

Figure 7.4: DQL routine for a lathe

7.4.3 DQL Simulation and Analysis

The total health risk for a given plant layout is determined from the output of the multiple DQL routines. The DQL of each process is determined which enables the most risky process to be identified.

This provides the opportunity for these processes to be modified, reducing the risk by for example using safer machines, and wearing efficient PPE. Production economics have been considered in this methodology to optimise productivity, resource arrangement, and work procedures.

Most of the working activities in our workshop case were associated with *lathe and mill*, hence this paper mainly focused on these two types of machines and related hazards and corresponding biological consequences. We designed three scenarios to explore using the DQL and simulation methodology, see Table 7.1. Scenario No.1 is the current status quo. Scenario No.2 and Scenario No.3 are the optimisation plans.

Scenario Name	Description	Changes to the plant model
Scenario No.1	10 students in the simulation. Activities are with 6 lathes, 4 mills, 2 drills and some hand tool activities.	No changes
Scenario No.2	10 students in the simulation. Associated activities are with 4 lathes, 6 mills, 2 drills and some hand tool activities.	Changed quantities of various machines. No changes to production or health parameters.
Scenario No.3	10 students in the simulation. Associated activities are with 6 lathes, 4 CNC mills, 2 drills and some hand tool activities.	Compared to Scenario 1, the manual mills are replaced with CNC mills. New tasks e.g. CNC programming were setup in each activities with different processing time, and set up time. No changes at workflow. Frequency, and likelihood at DQL were changed at DQL routine.

Table 7.1: Scenario descriptions

Mill, lathe and CNC machines were analysed by the DQL simulation methodology. DQL estimates were provided by the workshop manager and the authors. The full application of DQL instruments is contained in Appendix A. An extract of lathe analysis is shown in Table 7.2.

Diminished Quality of Life (DQL) Instrument							
A	B	C	D	E	F	G	H
Standard hazard categorisation, used as checklist by industry	*Severity Context is added by engineering technologist*	*Sub-category of column A per ontology*	*Estimate provided by engineering technologist or H&S officer*	*Sub-category of column C per ontology*	*Estimated by Occupational Hygienist or H&S officer*	*Derived from WHODAS*	*Computed (DxFxG)*
Hazards in Workplace	**Severity Context and current state**	**Incident Description** *(S: Safety Accident H: Health Issue)*	**Frequency of a single Incident arising in your working career at this site (Estimated for the workplace)**	**Biological Consequence**	**Likelihood of Consequence arising (Estimated for this workplace)**	**Consequence: Level of Harm (WHODAS)**	**Diminished quality of life (DQL)**
Chemical Exposure	Coolant and lubricating oil	H: Long term chemical exposure work environment	60%	Skin disease, e.g. dermatitis	50%	2.08	0.62
				Respiratory system compromise	30%	2.08	0.37
				Blood pressure compromise	7%	10.42	0.44
		S: Exposure to eye	30%	Eye injury	60%	12.50	2.25
		S: Exposure to skin	60%	Skin damage	50%	2.08	0.62
Cutting, Crushing and Squashing	Machine tools, open (not enclosed)	S: Accidentally injured by machine	50%	Amputation (arm, finger, foot, hand, and leg)	30%	47.92	7.19
				Lacerations	50%	14.58	3.65
				Bone injury	30%	17.92	2.69
				Death	7%	100.00	3.50
		S: Accidentally injured by hand tools	30%	Abrasion	50%	0.00	0.00
				Amputation (arm, finger, foot, hand, and leg)	7%	47.92	1.01
				Bone injury	30%	47.92	4.31
		S: Accidental bodily injury by foreign objects	50%	Lacerations	30%	14.58	2.19
		S: Accidental eye injury by foreign objects	30%	Eye injury	30%	64.58	5.81

Table 7.2: DQL result for the lathe

The analysis shows that the lathe and mill have different risks and hence consequences. These could be reduced for example by using a CNC machine. Activities with a higher risk for the mill are:

- Changing cutter: This requires people to use a spanner to loosen the drawbar and then use a hammer to tap the drawbar and after changing the cutter, then use spanner to tighten the drawbar. This activity may require people to climb and reach near the top of the mill, which could become a hazard, and result in trips and falls. Another hazard could be being hit by hammer, and this could result in abrasion, and bone injury.
- Cut by a foreign object: This could be caused by material waste and exacerbated by mechanical failure of the cutter or material.
- Jamming: Some loose item such as cloths, could be caught while operating the mill. This could become an H&S issue and result in abrasion, amputation, bone injury, or even death.

Simulations in Scenarios No.1, No.2 and No.3 cover two major hazards at work: (a) chemical exposure and (b) cutting, crushing and squashing. The corresponding eight biological consequences were addressed in the simulation. We ran simulations for each scenario 200 times. Table 7.3 shows the mean DQL result for each scenario. We used a simple additive sum to determine the total health risk, on the basis that all the health outcomes are simultaneously possible (i.e. one outcome does not preclude the other). To some extent this assumes that the individual DQL categories are independent of each other, which is approximately true to a first approximation.

Scenario Name	Scenario No.1	Scenario No.2	Scenario No.3
DQL Amputation	41.1	41.5	28.8
DQL Blood Pressure Compromise	1.9	1.9	1.7
DQL Bone Injury	22.6	23.0	14.6
DQL Eye Injury	15.9	16.3	12.3
DQL Lacerations	24.9	25.8	18.7
DQL Respiratory System Compromise	1.3	1.3	1.2
DQL Skin Damage	2.1	2.1	2.3
DQL Skin Disease	2.4	2.4	2.2
Total DQL Score [sum]	**112.0**	**114.2**	**81.7**

Table 7.3: DQL risks for 200 simulations

There are no significant differences for the DQL results between Scenario No.1 and Scenario No.2, see Table 7.4. Probably the working environment and operation activities at lathe and mill in the case are similar to each other. However, Scenario No.2 benefits the system in another way. With the changes in machine arrangement, the production related factors such as waiting time were also changed. The simulation results showed that the average waiting time of Scenario No.2 is 73.5 minutes less than Scenario No.1. During this time the students could conduct other training activities. Waiting is potentially a hazard in a workshop, as bored students introduce new hazards (although we did not explicitly model these). Hence reduction in waiting time is beneficial from the perspective of reducing boredom. The reduced waiting time can also benefit students' learning, and potentially course satisfaction.

Scenario Name	Scenario No.1	Scenario No.2	Scenario No.3
Average Waiting Time (minutes)	274.9	201.4	274.8
Average Students' Working Time (minutes)	919.4	848.8	921.8
Average Total Course Teaching Time (minutes)	2160.0	2160.0	2160.0

Table 7.4: Time cost in different scenarios

The average DQL metrics are instructive, but it is also valuable to examine the variability therein. Hence boxplots were determined for the various biological consequences. An extract of DQL Boxplot analysis is shown in Figure 7.5, for the other boxplot diagram see Appendix B.

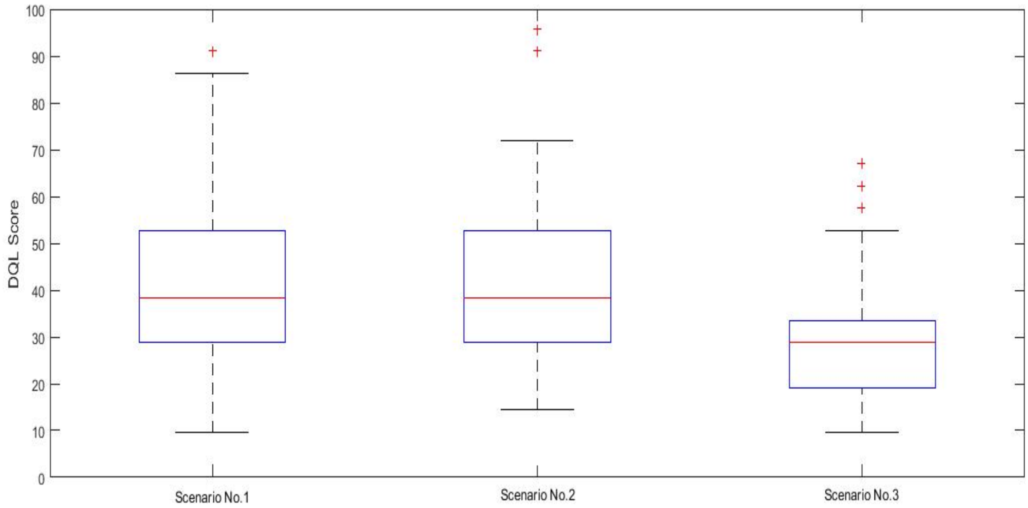

Figure 7.5: DQL boxplot analysis for amputation, for Scenarios No.1, No.2, and No.3. The boxplots show the median, 99.65%, 50%, and 0.35% percentile ranges. Middle crosses are outliers.

The boxplot analysis shows that Scenarios No.1 and No.2 have similar median DQL, but Scenario No.2 has less variability in outcomes. From a quality perspective, reduction in variability is a positive outcome, as it means the process is more controlled. From a safety perspective we are particularly interested in reducing the upper 99.65% limit (where the DQL is worse). From this criteria Scenario No.2 is better than Scenario No.1 (the status quo) regarding amputation, eye injury and lacerations; no worse regarding blood pressure compromise, bone injury, respiratory system compromise and skin damage; and worse regarding skin disease.

However, as purely productivity optimisation, Scenario No.3 did not show significant improvement in total working time and waiting time. The CNC machines generally have a better performance in production efficiency rather than the manual milling machines, but not in our case. This is because in our workshop the operators are first-time users, hence the set-up time (CNC programming) has to be redone for each job, and is dependent on their learning ability.

Nonetheless the DQL scores for Scenario No.3 are universally better than Scenarios No.1 and No.2 regarding lower median, and lower upper 99.65% limit (with exceptions for skin damage). This is attributed to the CNC machine providing a safer working environment for the following reasons:

- Sufficient barriers to keep the cutter, foreign objects, and waste inside a secured area. Loss items e.g. cloth, may jam the cutter, and cause further harm to a person's body. This could result in lacerations, amputations, and even death. Some foreign object may hit a person's body during mill operation by for example improper machine operations.

- Less physical activities while operating a CNC rather than a mill. CNC machines are controlled by programmed instructions. Manual operations associated with milling machines include changing cutter, and manual controls. These activities could result safety issues, e.g. trips and falls when changing cutter, and fatigue related musculoskeletal issues.

7.5. Chapter Discussion

7.5.1 Summary of Novel outcomes

The conventional safety risk methodologies mostly focus on managing safety accidents (short-term effects). Compared to safety accidents, health issues are difficult to anticipate. This is because health problems are more complex, i.e. frequency and likelihood are difficult to estimate. Also, the corresponding biological consequences may take time to develop, may be affected by multiple factors, and the injuries may be permanent. The previous research on DQL was focused on a single workstation, e.g. a lathe, and the risk of OHS was calculated via Excel spreadsheet [2]. It is relatively easy to model such simple scenarios; however, a larger manufacturing process can rapidly become more complex. This is where software support is helpful.

A new methodology in the form of the PSS has been developed. It provides an integration of OHS risk and plant simulation. In current software embodiment, it involves a set of programme sub-routines which are added manually to the plant simulation, thereby enabling the OHS risk of each activity to be determined.

7.5.2 Limitations of the Work

A current limitation of the DQL routine is the need to manually input data for frequency, likelihood, and WHODAS score. This requires users to have skills and experience in both DQL methodology and plant simulation programming. To minimise these difficulties the DQL routines have been designed in a simple linear way as an extra programme routine, separated from the main simulation.

Another limitation was the subjective judgement of frequency and likelihood. This is common to most risk management and plant simulation methods. Quantitative research may be required for accessing a person's subjective safety description.

7.5.3 Further Research

Future work could involve *time* as an attribute in safety and simulation methodology. This is currently limited by the inadequate literature on health consequences and time aspects. For example, some health consequences (e.g. hearing loss) can be cumulative, and difficult to detect the exposure time duration. The current DQL methodology is developed based on subjective judgment of the *frequency of the incident arising* for a reasonable working duration. This might be improved by future research which focused on the long-term evolution of occupation health consequences.

Another possible line of future research could be to more tightly integrate DQL with plant simulation software. This would require access to source code. The present method does the

DQL analysis in a separate spreadsheet, and it would be helpful for the user if a user-friendly interface were available.

7.6. Chapter Conclusions

Conventional approaches to plant simulation are primarily focused on maximization of economic utility. In parallel all plants have health and safety risks, which need to be managed. However, the economic and safety optimisations tend to be independent processes. Furthermore, most risk assessment methods used in plants are based on safety (prevention of accidents), and the long term health outcomes have received less attention. This work shows the development of a methodology that integrates health and safety considerations into plant simulation. This has the potential to provide a new and better integrated approach to understanding the interaction between the economic and health dimensions in plant optimisation.

Chapter 8: A Methodology Simulating Production Economics and Safety Risk in SMEs: A Case Study in the Food Industry

8.1 Chapter Introduction

Small and medium enterprises (SMEs) often originate from product innovations. The long-term growth of SMEs depends critically on their ability to transition and grow as organisations, and this needs development of appropriate systems. However, the existing methodologies for production economics and Health and Safety (H&S) risk management are applied disjointedly. Moreover, growth of SMEs introduces new challenges because production does not scale linearly, and organisational systems have to be extended. SMEs typically increase productivity, which requires capital investment and changes to the structure of their operational management systems. Making changes to operational system not only changes production economics, but also impacts on H&S. Complexity arises because manufacturing operations are nonlinear and many H&S risks such as respiratory disease, and musculoskeletal injury are difficult to manage. Cause identification is also difficult, especially measuring the corresponding likelihood and frequency. Integrating these into a holistic decision-framework is non-trivial and has not been demonstrated. The methodology presented here has potential to assist with SME growth decisions, specifically in the complex investment mix of hardware and labour, and the concomitant effect of operations on societal outcomes as measured in H&S. The methodology presented is an integration of DQL and plant simulation, which provides a quantitative way to manage production economics and H&S risk.

Existing H&S risk methodologies are primarily focused on reducing consequence and likelihood of the safety accidents [21] [64], but have limitations in managing long term health issues [1] [2]. Many long term health issues, for example, respiratory disease [339], and musculoskeletal disease [340] occur due to cumulative exposure, which increase the difficulty of identification and prevention [341]. Hence some existing safety accident preventions become inefficient when dealing with chronic health issues [342]. Existing production economics research focuses on improving productivity [3], but pays little attention to the management of H&S risk [9]. Plant simulation is widely used in system optimisation, especially in the area of production planning [3] [343], data based decision-making [344], and uncertainty analysis [345]. Existing methodologies are described based on discrete-event simulation (DES) [6] [346], and Monte Carlo sampling [320] [347].

Food production such as bakery has many different activities, for example, oven cooking, bread forming, and packing [348]. Typical hazards include repetitive movement, dusty [349] [350], sensitization [351], and chemicals [352]. Cumulative biological consequences include respiratory system compromise [264], musculoskeletal injury [353], hearing loss [32] [354], and skin damage [278]. These hazards are typically addressing balanced work-break schedules [355], efficient PPE [339] [356], and ergonomic workstations [31].

There is a need to anticipate the H&S issues while addressing productivity. The integration of DQL and plant simulation methodology has the capacity to simultaneously manage production economics and H&S risks in the content of a SME and in the particular case of a food production facility (bakery).

8.2 Research Approach

8.2.1 Preamble

A methodology is described which enhances management systems to support SME growth, by integration of production economics, and health and safety risk management. The methodology has been validated for the case of a bakery. The workflow is shown in Figure 8.1.

Production parameters are:

- The production line produces 12000 savouries / 200 trays lots per day. A savoury is a type of meat pie.
- Cooked meat is used one day after being chilled.
- Cooked savouries are packed one day after being chilled.
- Staff have a 20 minutes break after working 2 hours.
- Other staff will do the preparation work during the break time.
- The ovens can take 10 trays at a time.
- The potato topping process is operated manually.
- The bakery wishes to reduce the occurrence of musculoskeletal injuries.

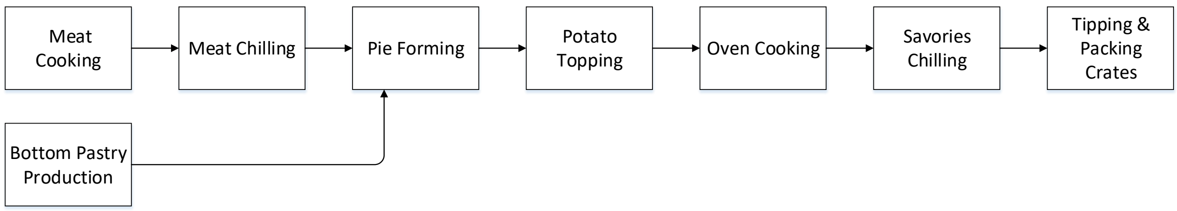

Figure 8.1: Workflow for Cottage Savouries

8.2.2 Methodology

A safety induction was firstly introduced by the SME and this was followed by onsite observations. The observation included collecting information related to the production economics (for example, plant layout, workflow, potential improvement plan, and time distribution) which was then used for developing the simulation model. The time distribution of each process was provided by the SME.

H&S information was then collected using DQL methodology. Estimations of the frequency and likelihood of incidents were generated in consultation with the H&S representative of the SME. Biological consequences were determined by DQL methodology using WHODAS 12-items [2].

An initial simulation for the status quo was then developed using Arena software (Version 16.0) which is based on discrete-event simulation (DES). A DQL routine was employed to combine the plant simulation with the associated H&S risk. The DQL routine consisted of three parameters: frequency of the incident, likelihood of the consequence, and level of harm. These parameters were collected using DQL. The routine was created in the Arena simulation using assign model, decision model, routine and station. The simulation provides the final OHS risk result. An improvement plan of the simulation was then generated after discussion with the plant manager, production engineers, and H&S representative.

The DQL risk and production economics related results such as process time were then compared to the status quo and improvement plan. Boxplots analysis was used to manage DQL results for each biological consequences and scenario. Capacity flexibility was then determined based on the improvement plan.

8.3 Results

8.3.1 H&S Risk Analysis

The H&S risk of each operation in the bakery process was determined using DQL methodology [2]. This was then modelled using simulation of the plant. Two scenarios were modelled with the objective of optimising the H&S risk associated with savouries production, see Table 8.1.

Scenario name	Description	Identity of the model
Scenario No.1	Status quo. The original savouries production line, including manual potato topping.	Five staff manually executing the potato topping process.
Scenario No.2	Automatic potato topping machine is used for topping process. The topping machine is able to top 3 savouries per second.	Only one member of staff is required for loading ingredients into the machine

Table 8.1: Scenario descriptions

Scenario No.1 is the status quo which consisted of five staff conducting by hand the potato topping. Scenario No.2 is the estimated optimised plan employing an automatic topping machine instead of manual topping. Compared to the status quo, only one staff is then needed for loading the ingredients into the machine.

The H&S risk of Scenario No.1 and No.2 was determined using DQL methodology, see Table 8.2. The same method was applied to all the other processes in Figure 8.1, and then aggregated to determine an overall health score.

Diminished Quality of Life (DQL) Instrument							
A	B	C	D	E	F	G	H
Standard hazard categorisation, used as checklist by industry	*Severity Context is added by engineering technologist*	*Existing barriers xxxxx Sub-category of column A*	*Estimate provided by engineering technologist or H&S officer*	*Sub-category of column C per ontology*	*Estimated by Occupational Hygienist or H&S officer*	*Derived from WHODAS*	*Computed (DxFxG)*
Hazards in Workplace	**Severity Context and current state**	**Incident Description** *(S: Safety Accident H: Health Issue)*	**Frequency of a single Incident arising in your working career at this site (Estimated for the workplace)**	**Biological Consequence**	**Likelihood of Consequence arising (Estimated for this workplace)**	**Consequence: Level of Harm (WHODAS)**	**Diminished quality of life (DQL)**
Dust	Pastry making, low exposure to flour dust	Face marks are available.	30%	Lung infection, chronic lung disease	30%	2.08	0.19
Impact Damage	Moving plant (forklifts but not in the room itself), trolleys, falling trays or flour bags	Feet potected by steel toe cap. Trolleys operating in/around this location.	7%	Musculoskeletal injury	50%	8.33	0.29
Trips, slips and falls	Sliper floor, close to the cleaning station, unclean/wet floor	Trips at floor	60%	Musculoskeletal injury	50%	8.33	2.50
				Lacerations	50%	4.17	1.25
				Eye Injury	30%	12.50	2.25
				Bone injury	50%	8.33	2.50
Manual Heavy Loads and Repetitive Work	Maximum load 10kg	H: Moving heavy objectives; or long-time repetitive work, e.g. potato topping	90%	Muscle damage, tendon and ligament injury	60%	8.33	4.50
Noise	Occasional noise levels over 65 dB, ear plugs voluntary	H: Caused by machine operating	1%	Hearing loss	1%	12.50	0.00
Temperature	Burns from ovens;Reasonable temperature control system applies	H: Uncomfortable temperature Environment	1%	Circulatory system diseases	1%	8.33	0.00
				Musculoskeletal injury	1%	8.33	0.00
Uncomfortable Working Position	Possible bent neck when operating machine	H: Long term work in uncomfortable position	60%	Muscle damage, tendon and ligament injury	50%	8.33	2.50

Table 8.2: DQL result of manual potato topping process

The average DQL result of each biological consequence was then determined by the simulation and taken as the arithmetic mean. The simulation of each scenario ran 200 times. The average DQL result of each biological consequence is shown in Table 8.3. The level of harm of each consequence were then determined based on the DQL thresholds [2], see Table 8.4.

A consequence such as 'Chronic or overuse muscle and soft tissue injury' may arise from multiple causes. There are several possible ways to interpret this situation. The overlapping consequences and how to combine the DQL scores become the limitation. A worker can be exposed to different hazards and consequences at the same time, which is complex. There are several possible solutions to interpret this situation:

(a) It could be argued that only the worst case should be used, on the basis that the worker is only exposed to one such incident at any moment in time. This might apply especially to minor to moderate accidents, but seems less relevant to chronic exposure that may affect multiple body systems at once.

(b) Another interpretation is that the DQL risks should be combined using reliability theory, based on the likelihood of occurrence. This because the chance of all these occurring simultaneously is remote.

(c) Another option could be to add all DQL risks of same origin, on the basis that a worker is exposed to them all during the course of a period of time. The fact that one injury occurs does not prevent another different injury occurring. However, to sum DQL risks from the same origin makes a tacit assumption that the underlying physiology, e.g. nerve compression, follows a simple additive law. Even if nerve compression were to accumulate in that way, it does not follow that injuries to other body systems will do in the same way. There may be non-linearities, threshold effects, saturation/plateau behaviours in system responses. This type of complex system behaviour is known in the area of toxicity response (dose response dependencies), but is only partly developed in the area of chronic injuries. Furthermore, some of the dependencies, e.g. for occupational overuse syndrome, appears to be related to psychosocial factors. There is a future need to better understand the exposure response dependencies for a variety of chronic harms. It would also be necessary to have a finer-grained DQL analysis.

Here, the DQL result for multiple occurrences is determined using solution (c). This is because these corresponding hazards diminished a person's life score in long term period and occurred by cumulative exposure. The two categories, Traumatic Musculoskeletal injury, and Chronic or overuse muscle and soft tissue injury, were combined into Musculoskeletal injury. This is because the cause of these consequences are cumulative.

In both Scenario No.1 and Scenario No.2, bone injury, circulatory system disease, eye injury, hearing loss, lacerations, respiratory system compromise, and skin damage risks were determined as low-level harm with no further treatments required. The DQL result of the hearing loss was found to increase in Scenario No.2, this is because comparing with manual topping, noise may arise during the machine operation, with a long-time exposure, this may cause further potential hearing loss. However, the level of the DQL is low, hence no further treatment is needed. Musculoskeletal injury was determined as 'moderate level' for Scenario No.1, and as 'low level' for Scenario No.2. The decrease of DQL was due to the changes at potato topping process.

Scenario Name	Scenario No.1	Scenario No.2
DQL Bone Injury	0.41	0.34
DQL Circulatory System Disease	0.02	0.02
DQL Eye Injury	0.37	0.31
DQL Hearing Loss	0.21	0.22
DQL Lacerations	0.21	0.17
DQL Musculoskeletal injury	**1.14**	**0.81**
DQL Respiratory System Compromise	0.02	0.01
Total DQL Score [sum]	**2.36**	**1.88**

Table 8.3: DQL risks for 200 simulations

DQL Result	DQL Level	Preventative Mechanisms
0-1	Low	No further treatments required.
1-3	Moderate	Implement treatment in a reasonable time period.
3-8	High	Implementation of treatment required.
Over 8	Extreme High	Unacceptable risk. Need urgent treatment.

Table 8.4: DQL thresholds

The average DQL metrics are instructive, but it is also important to examine their variability. Boxplot methodology was used to determine the various biological consequences. An extract of DQL Boxplot analysis of musculoskeletal injury in different scenarios is shown in Figure 8.2. The boxplot analysis shows Scenario No.2 has a better DQL than Scenario No.1 with good H&S risk control. The improvement plan using automation of the topping process has a decreased risk of musculoskeletal injuries.

As production increases, the hazard exposure time increase, and consequently the frequency and H&S risk increase. This issue can be managed by:

- Different work-shifts would decrease the frequency of hazard exposure per worker. However, this may increase the difficulties of human resource management such as recruitment of workers, and may add additional cost such as training.
- The productivity of the system could be improved to reduce the frequency. This reduces the exposure time to hazards by improving the productivity. These methods may add cost.

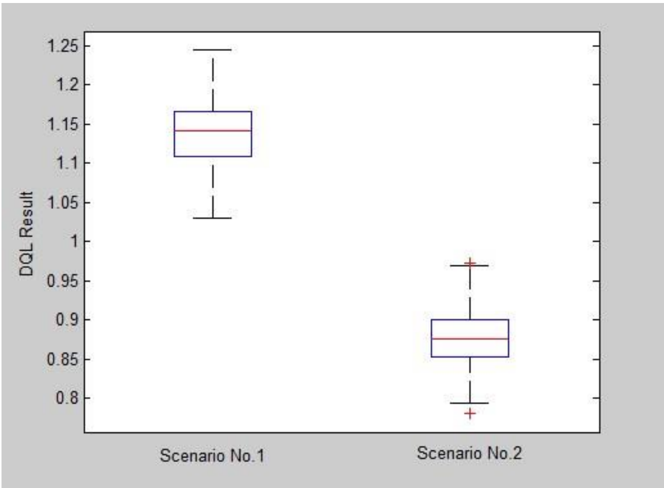

Figure 8.2: DQL boxplot analysis for musculoskeletal injury are outliers.

8.3.2 Validation of the DQL method

The validation of the DQL results was developed by a qualitative validation with industry.

The above DQL results were presented to the H&S representative and operations manager. The results were then discussed. The staff were positive about the results, felt that they were realistic representations of the health risks, and that the method had value.

The researcher sought specific comments on a number of questions. These and the paraphrased responses are given in Table 8.5.

The results show that the DQL method, combined with plant simulation, was perceived to be a useful methodological innovation. Additionally, these positive comments also show that DQL is a reliable safety risk management methodology, especially with a reasonable ability to identify the long-term (chronic) health issue.

Question Number	Question Descriptions	Comments from H&S representative
Q1	How do you think DQL result of Scenario No.1 addresses the health risk in the manual potato topping process?	'This is a good quality result. Comparing to the original risk methodology, DQL method measures H&S risk with a special focus on long term health issues, e.g. musculoskeletal injury.'
Q2	How do you think this DQL result of Scenario No.2 addressed the health risk in the automation potato topping process?	'Scenario No.2 is an estimation if using automation machine instead of manual activities in potato topping. The DQL result is reasonable and reliable which also allow us to foresee the H&S consequences.'
Q3	Do you think DQL could be a quality methodology to measure H&S risk at workplace?	'Yes. DQL has the ability to measure long term health issues with a special focus on corresponding frequency and likelihood. WHODAS is also a reliable tool to manage the biological consequences.'

Table 8.5: Discussion and comments

8.3.3 Productivity Capacity Optimisation for SME Growth

The growth trajectory is difficult to manage, especially for SMEs. Productivity requires capital investment and changes to the structure of their operational costs. This needs to be sustained in the main by profit. Furthermore, production does not always scale linearly; systems cannot always be run faster to produce more goods. Consequently, new manufacturing facilities are often required together with more workers with different skillsets. Therefore, uncertainty may arise when changes are made to one part of the whole system. This is because many SME manufacturing systems are designed based on the theory of lean and theory of constraints (TOC). Hence, making changes at a TOC system is following the 'domino effect'. Therefore, it is necessary to examine the performance of each process before making real change. There are many important parameters such as machine utilisation, resource layout, and process time.

Production Capacity Analysis

The time cost of different production processes in the current system for Scenario No. 1 and No. 2 were determined by the simulation, see Table 8.6 and Table 8.7. The potato topping process was found to have a significant decrease in the average waiting time compared to Scenario No.1 and Scenario No.2. TOC management [357] was applied here, hence automation topping machine was set as the same speed of the average manual topping operation (same value adding time). However, according to the operation manager, the difference arises because the machine does not need a regular break during the production. And with regular checks and appropriate maintenance, the machine is very unlikely to have a failure during production, hence compared to manual topping this results in a constant and reliable production speed, and further results in reduced waiting time.

Production Processes	Average Value Adding Time/Tray/Hours	Average Waiting Time/Tray/Hours	Average Total Time/Tray/Hours
Pie Forming	0.01	1.05	1.06
Potato Topping	0.01	0.36	0.37
Cooking	0.23	0.01	0.24
Tipping and Packing	0.01	1.56	1.57

Table 8.6: Time distribution of at Scenario No.1

Production Processes	Average Value Adding Time/Tray/Hours	Average Waiting Time/Tray/Hours	Average Total Time/Tray/Hours
Pie Forming	0.01	1.05	1.06
Potato Topping	0.01	0.00	0.01
Cooking	0.23	0.07	0.30
Tipping and Packing	0.01	1.56	1.57

Table 8.7: Time distribution at Scenario No.1

The waiting time for the oven cooking process for Scenario No.2 was found to increase, see Figure 8.10. This is because the total time spent on the pie topping process decreased significantly, hence more uncooked pies arrived at the cooking process and this resulted in an increase in the waiting time. It may be acceptable but with large orders long waits may be incurred.

Effect of Additional Hardware

Scenarios with additional hardware (for example, additional ovens, and pie forming machines) were then considered, to determine the productivity bottleneck [358] of the current system, and develop productivity improvement plan. Demand loading in the status quo (scenario 1) was 12,000 pies per day. A growth strategy was considered of incrementing this to multiples of 12,000, see Table 8.8. Each scenario ran 200 times.

The packing process was not considered because:

- The target company separates the pie making process with the packing process
- The cooked pie must be chilled one day before packing.
- A flexible operation method was applied in the packing process which is using automation picking machine when dealing with large orders.

Scenario Names	Demand loading (pies/day)	Number of Ovens	Number of pies forming machine	Scenario Descriptions
Scenario No.1	12000	1	1	Status quo, manual potato topping
Scenario No.2	12000	1	1	Automatic potato topping
Scenario No.3	24000	1	1	Automatic potato topping
Scenario No.4	36000	1	1	Automatic potato topping
Scenario No.5	48000	1	1	Automatic potato topping
Scenario No.6	12000	1	2	Automatic potato topping
Scenario No.7	24000	1	2	Automatic potato topping
Scenario No.8	36000	1	2	Automatic potato topping
Scenario No.9	48000	1	2	Automatic potato topping
Scenario No.10	12000	2	2	Automatic potato topping
Scenario No.11	24000	2	2	Automatic potato topping
Scenario No.12	36000	2	2	Automatic potato topping
Scenario No.13	48000	2	2	Automatic potato topping
Scenario No.14	60000	2	2	Automatic potato topping

Table 8.8: Scenario information

Significant waiting times occurred in the pie forming process and cooking process when the demand loading increased, see Table 8.9 and Figure 8.3. The waiting time reduction scenarios were determined by adding or removing resources. Waiting time associated with cooking process had a significant increase for Scenario No.6, No.7, No.8, and No.9. These scenarios were not considered further because the arrangement with a consequent extended waiting time.

	Pie Forming (Unit: Hour)	Potato Topping (Unit: Hour)	Cooking (Unit: Hour)	Total waiting time (Unit: Hour)
Scenario No.1	1.05	0.36	0.01	**1.42**
Scenario No.2	1.05	0.00	0.07	**1.12**
Scenario No.3	2.11	0.00	0.15	**2.26**
Scenario No.4	3.16	0.00	0.22	**3.38**
Scenario No.5	4.24	0.00	0.30	**4.54**
Scenario No.6	0.50	0.02	0.50	**1.02**
Scenario No.7	1.10	0.05	1.10	**2.25**
Scenario No.8	1.60	0.08	1.70	**3.38**
Scenario No.9	2.10	0.11	2.30	**4.51**
Scenario No.10	0.50	0.03	0.01	**0.54**
Scenario No.11	1.10	0.05	0.02	**1.17**
Scenario No.12	1.60	0.08	0.03	**1.71**
Scenario No.13	2.10	0.11	0.04	**2.25**
Scenario No.14	2.64	0.14	0.06	**2.84**

Table 8.9: Average waiting time at different scenarios

The threshold for total production time with different machine arrangement can be determined from (1).

$$\text{Production Time} = \text{Value Adding Time} + \text{Waiting Time} \quad (1)$$

The total time for pie production for different scenarios is shown in Figure 8.13. Unacceptable total production time was assumed to be 24 hours. The total time was linear as a function of production rate. Hence, the production capacity of the machine arrangement with one pie forming machine and one oven was determined to be 38,741 pies per day; the production capacity of the machine arrangement with two pie forming machine and two ovens was determined to be 60,225 pies per day.

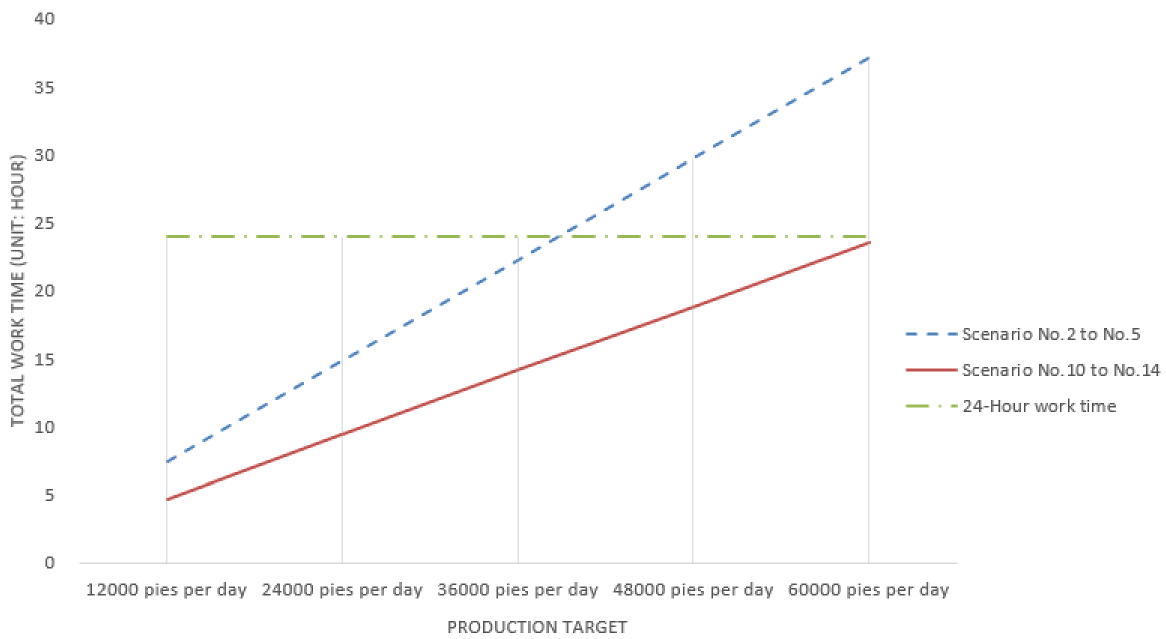

Figure 8.3: Production target and total time

Capital Investment

Capital investment plans were determined based on two scenarios, see Table 8.10.

Machine Arrangement		Capital implications for volume growth	Labour implications for volume growth
Scenario No.2	One pie forming machine, and one oven. Includes pie topping machine.	None.	Extra workers required to be recruited for different work shifts.
Scenario No.10	Two pie forming machine, and two ovens	Requirement to purchase one oven, and one pie forming machine.	Extra workers required to be recruited for different work shifts.

Table 8.10: Machine arrangement plan

The profit can be expressed by (2) and (3) below, ignoring depreciation:

Annual profit=Total pie profit – Total workers' salary – Cost of adding machine (2)

Total workers' salary= Rate per hour × Total production time (3)

The profit of different arrangements with different production target were then determined, see Figure 8.4. Nominal assumptions, are listed below:

- Sufficient storage space available;
- The cost of a pie forming machine is $10,000;
- The cost of an oven is $10,000;
- The profit of one pie is $0.1;
- The cottage production system has 5 workers;
- The salary rate of the workers is NZD $20 per hour;
- The factory operates 300 days per year;

- We focused on cottage pie making process, hence worker's working time is determined by the total time of the cottage pie making.

Scenario No.2 has a linear increase with the profit and then becomes flat when the production target is around 36,000 pie per day, this is because the daily production capacity of Scenario No.2 is 38,741 pies, and hence the limitation of Scenario No.2 is dealing with large orders. The advantage of Scenario No.2 is in a situation where the growth is uncertain (usually this depends on the order), it offers a way to increase production (up to 36,000 pies/day) using labour. Another advantage is Scenario No.2 requires no more investment.

The profit associated with Scenario No.10 also shows a linear increase, but the amount of profit is higher than for Scenario No.2 for every production target. Alternatively, the profit difference between Scenario 2 and Scenario 10 is minor when the production target is small e.g. 12,000 pie per day, however, become significant when the production target is larger. The trend becomes flat when the production target is around 60,000 pies per day, this is due to the production capacity of Scenario No.10 (60,225 pies per day). Therefore, we propose when the daily pie production target is under 60,225, Scenario No.10 has benefits with a larger production capacity and greater annual profit; if the daily pie production target is larger than 60,225, the system meets the bottleneck at production and needs an improvement. Advantage of Scenario No. 10 is in a situation where the growth is certain, it offers a way to increase production (up to 60,000 pies/day) by adding one pie forming machine and one oven.

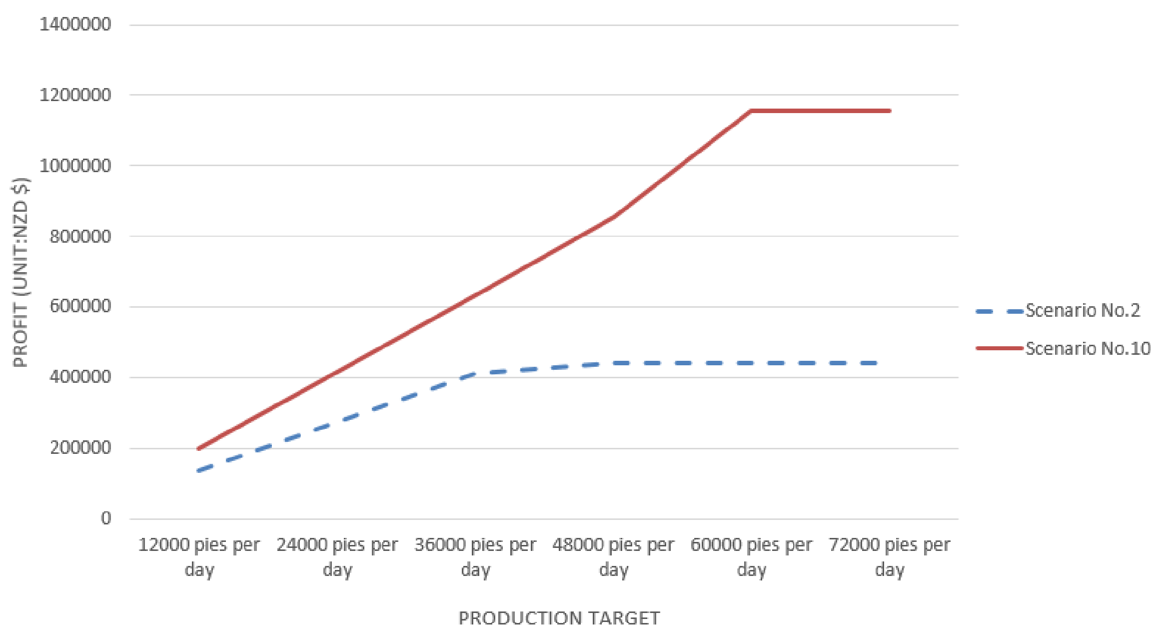

Figure 8.4: Profit analysis

8.4 Chapter Discussion

Economic and safety consideration tended to be considered independent processes. Existing approaches to plant simulation are primarily focused on maximization of economic utility and with little or no focus on health and safety risks. A methodology has been described that integrates health and safety considerations and production economics (e.g. capital investment and production capacity) through plant simulation. The methodology here has the potential to provide a novel integrated approach to assist the management of production economics and H&S risk. H&S risks was determined in a quantitative way which may help in further risk management, especially in non-notifiable risks and residual risks. We propose the integration of risk management and production economics may further help SMEs grow in a sustainable way.

8.4.1 Summary of Novel Outcomes

A methodology for SME growth integrating H&S risk management and plant simulation methodology has been created and validated through a case study. Novel outcomes include:

- Production economics are incorporated in this methodology, including the analysis of waiting time, productivity capacity, and capital investment.
- Existing risk methodology is largely based on subjective assessment. Difficulties arise when managing cumulative-caused chronic issues. The integration of DQL and plant simulation methodology successfully addressed this through cumulative discrete event modelling.
- H&S risks are determined in a quantitative way. The integration of DQL and plant simulation offered a way to quantify these risks, and further allow management through quantitative methods.

8.4.2 Limitations of the Work

One limitation of this work is the need to manually input risk data. The simulation requires sound knowledge in modelling, hence difficulties may arise when adopting this integration methodology in industry. A potential way to solve this issue is to develop a user-friendly interface or an individual simulation software.

Although quantitative outcomes are presented by DQL, subjective judgement of frequency and likelihood are still required. This is a common issue in risk management. This was addressed by designing easily understand descriptions (quantitative) for users to understand frequency and likelihood categories.

8.4.3 Further Research

Food safety risk management is important area in the food industry. DQL methodology can be used to manage food safety along with workers H&S.

8.4.4 Generic implications for application of the method to industry

The integration of DQL and plant simulation requires an advanced knowledge of risk management and experience in plant simulation. Therefore, developing a software based on H&S risk management and productivity economics may provide a route to assist the adoption of this approach in industry.

The methodology described here can also be applied to other industries such as construction, mining, forestry, transport, and ports. The methodology of safety risk applied here may also be applicable to other uncertainties such as environmental risk.

A generic approach was developed for application, as shown in Figure 8.5. This starts with regular safety inductions and then collecting information via onsite observation. This is for plant simulation modelling. H&S information would then be collected using DQL. An H&S representative would determine the frequency, likelihood, and level of harm. These data would then be used to create a DQL sub-model for risk calculation. The result of the simulation includes H&S risk and engineering economics parameters, e.g. machine utilisation, profit, and cost. This information can be used to generate optimisation plans for reducing H&S risks and improving productivity. See also section 9.4 for a generalised method for integrating the method into conventional risk assessment.

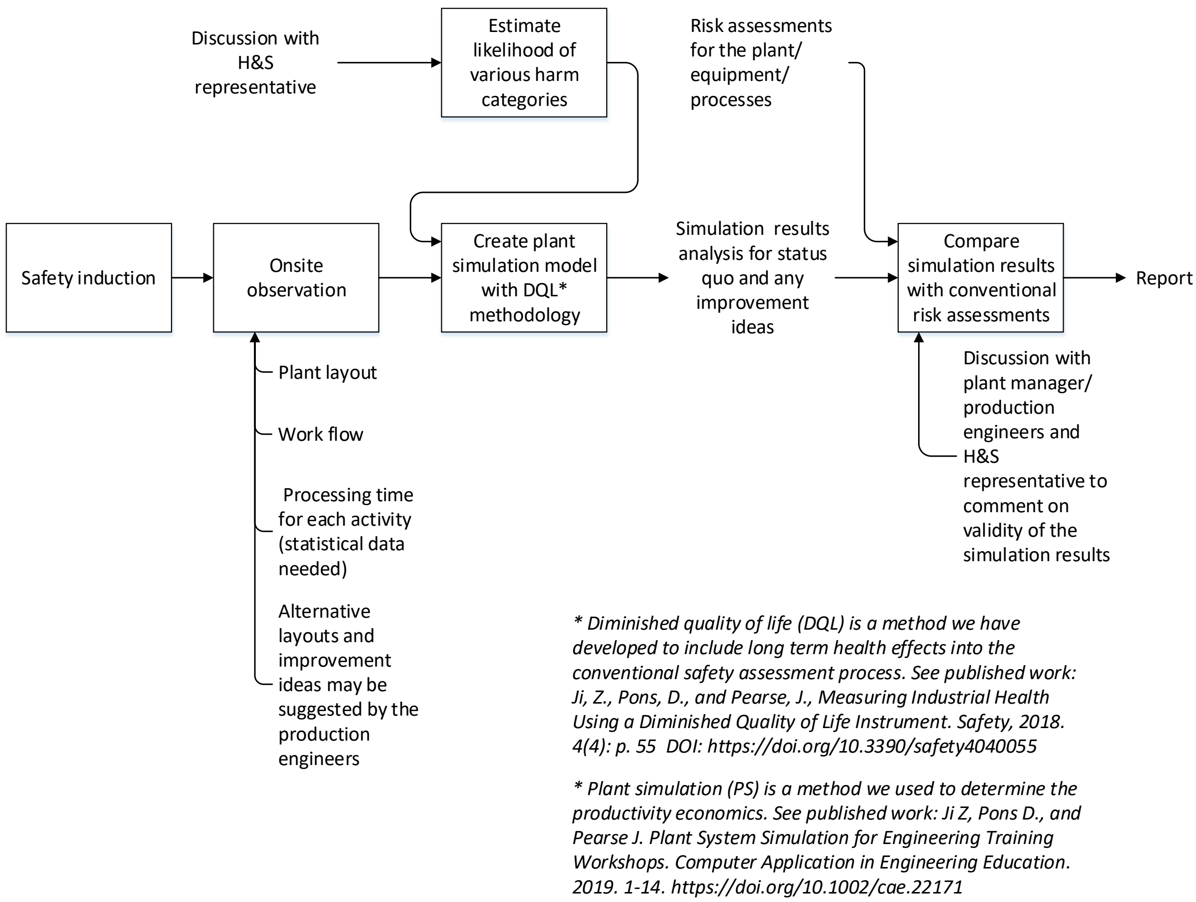

Figure 8.5: Suggestion approach for application in industry

Chapter 9: Developing a Methodology for Integrating both Health and Safety in the Risk Assessment Process

9.1 Introduction

The conventional risk assessment methods focus primarily on safety and the prevention of immediate incidents. They are, as established above, relatively weak at anticipating the chronic or long-term health implications. This is where DQL is more powerful, as it provides a means to determine adverse consequences in terms of quality of life.

An ideal methodology would combine the strengths of both. In fact, this is not difficult to achieve, and the DQL method should not be seen as oppositional to the conventional risk assessment method but rather an improvement. The integration may be achieved as follows.

First, it is necessary to have a set of risk decision-thresholds for the conventional method. These thresholds define risk tolerances (acceptable and unacceptable levels of risk) and the extent to which treatments become critical. Unfortunately, the conventional method does not have a standard set of such thresholds, nor is one evident in ISO 31000. Instead, each organisation develops its own, and hence the situation is ad hoc.

Qualitative explanation of likelihood	***Likelihood scale***							
Annual occurrence in this situation	*6 Almost certain*	60 +	48 +	30 +	24 +	18	12	6
Has occurred Several times in your career	*5 Likely*	50 +	40 +	25 +	20 +	15	10	5
Might occur once in your career	*4 Possible*	40 +	32 +	20 +	16	12	8	4
Event does occur somewhere from time to time	*3 Unlikely*	30 +	24 +	15 +	12	9	6	3
Heard of something like this happening elsewhere	*2 Rare*	20 +	16 +	10	8	6	4	2
Theoretically possible but not expected to occur	*1 Almost incredible*	10 +	8 +	5	4	3	2	1
Severity of harm (Consequence) hierarchy		**10. Catastrophe : (recovery systems inadequate, multiple deaths occur)**	**8. Death**	**5. Serious harm.** Incident results in serious harm (notifiable injury)	**4. Serious incident.** Incident occurs and exposure to serious harm (no actual harm arises) (notifiable incident)	**3. Minor harm.** Incident occurs and Minor harm results	**2.Incident without harm.** Incident occurs with no harm (system fails)	**1. Hazard in control.** Hazard present but existing controls prevent progression

Figure 9.1: Conventional risk matrix. Image from [1] reproduced by permission.

Nonetheless there has been a recent proposal to develop a standardised set of thresholds [1]. These thresholds were determined by application of a non-linear harm (consequence) scale.

Also, the consequence scale was designed to be consistent with the Health and Safety legislation of the country under examination (NZ), since lack of such consistency is another problem of the application of the conventional method. The conventional risk matrix and decision thresholds are shown in Figure 9.1 and Table 9.1.

Risk, R = C x L	Corresponding colour in risk map	Description	Principle of Action	Authority for continued operation	Reporting
30 or higher	Purple	Unacceptable risk.	Operations to cease until risk reduction is achieved. Ensure provenance of Disaster Recovery mechanisms in addition to Preventative means.	Board	CEO to advise Board as soon as practicable.
18 or higher	Red	Urgent treatment.	Urgent implementation of treatment required. Operations proceed with caution and ongoing monitoring of risk	CEO	Technical manager to advise CEO as soon as practicable, and report regularly on status of the risk and its treatment.
8 or higher	Yellow	Consider treatment	Implement treatment in a reasonable time period. Operations proceed, with monitoring to detect if risk becomes worse or persistent	Technical manager	Team leader to report periodically to Technical manager on the risk and the progress of the treatment plan.
7 or less	Green	No intervention necessary.	No further treatment required. Operations continue, with ongoing monitoring to check the efficacy of existing controls/barriers/procedures. Conduct periodic (e.g. annual) re-assessment of the risk.	Team leader	Staff to report periodically to Team leader on the state of this risk.

Table 9.1: Decision thresholds with actions and reporting expectations for conventional risk assessment, per [1] reproduced with permission.

9.2 Approach towards Creating an Integrated Method

It is necessary to align the DQL and conventional thresholds. A new risk matrix and an integrated scoring method was developed based on DQL and the conventional method.

Determining Likelihood Scale

Likelihood of harm was determined by incident event frequency and likelihood of harm consequences; this is based on series reliability and product of the frequencies, see Figure 9.2. In essence, we propose that the likelihood of harm is best determined as the product of how often the exposure event occurs, and how likely it is to cause health consequences. We propose the same probability scale for both, and suggest the range shown in the figure (100%, 60%, 40%, 20%, 10%, 1%) based on the work in Chapter 5 [2].

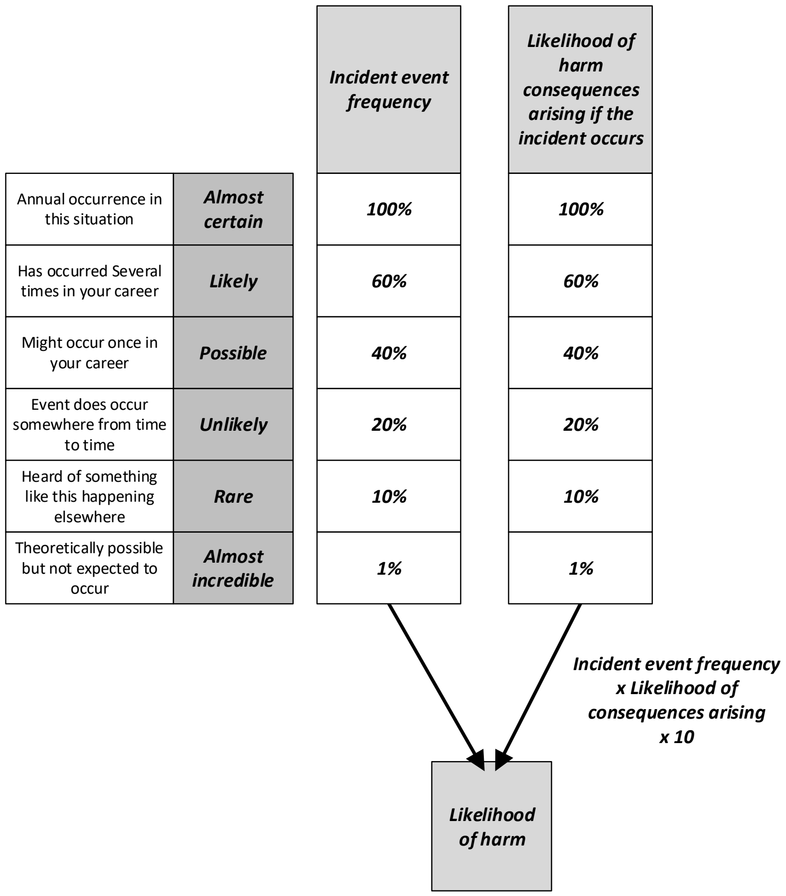

Figure 9.2: Method for computing Likelihood of harm

The spreadsheet representation of this is shown in Table 9.2, with columns D and F being the input frequencies, and H being the product. In this regard, nothing changes for the calculation of DQL score, except that the likelihood is needed explicitly for the purpose of integration with the conventional risk assessment process.

Diminished Quality of Life (DQL) Instrument								
A	B	C	D	E	F	G	H	I
Standard hazard categorisation, used as checklist by industry	*Severity Context is added by engineering technologist*	*Existing barriers xxxxx Sub-category of column A*	*Estimate provided by engineering technologist or H&S officer*	*Sub-category of column C per ontology*	*Estimated by Occupational Hygienist or H&S officer*	*Derived from WHODAS*	*Computed (DxF)*	*Computed (DxFxG)*
Hazards in Workplace	**Severity Context and current state**	**Incident Description** *(S: Safety Accident H: Health Issue)*	**Frequency of a single Incident arising in your working career at this site (Estimated for the workplace)**	**Biological Consequence**	**Likelihood of Consequence arising (Estimated for this workplace)**	**Consequence: Level of Harm (WHODAS)**	**Likelihood product**	**Diminished quality of life (DQL)**
Dust	Pastry making, low exposure to flour dust	Face marks are available.	30%	Lung infection, chronic lung disease	30%	2.08	9.00%	0.19
Impact Damage	Moving plant (forklifts but not in the room itself), trolleys, falling trays or flour bags	Feet potected by steel toe cap. Trolleys operating in/around this location.	7%	Traumatic Musculoskeletal injury	50%	8.33	3.50%	0.29
Trips, slips and falls	Sliper floor, close to the cleaning station, unclean/wet floor	Trips at floor	60%	Traumatic Musculoskeletal injury	50%	8.33	30.00%	2.50
				Lacerations	50%	4.17	30.00%	1.25
				Eye Injury	30%	12.50	18.00%	2.25
				Bone injury	50%	8.33	30.00%	2.50
Manual Heavy Loads and Repetitive Work	Maximum load 10kg	H: Moving heavy objectives; or long-time repetitive work, e.g. potato topping	90%	Chronic or overuse muscle and soft tissue injury	60%	8.33	54.00%	4.50
Noise	Occasional noise levels over 65 dB, ear plugs voluntary	H: Caused by machine operating	1%	Hearing loss	1%	12.50	0.01%	0.00
Temperature	Burns from ovens;Reasonable temperature control system applies	H: Uncomfortable temperature Environment	1%	Circulatory system diseases	1%	8.33	0.01%	0.00
				Traumatic Musculoskeletal injury	1%	8.33	0.01%	0.00
Uncomfortable Working Position	Possible bent neck when operating machine	H: Long term work in uncomfortable position	60%	Chronic or overuse muscle and soft tissue injury	50%	8.33	30.00%	2.50

Table 9.2: Reversed DQL spreadsheet

We then re-appraised the likelihood of harm scale, and found that it lacked a clear progression in terms of ranked order, see Figure 9.3. It was observed that the logarithmic fit was not particularly good.

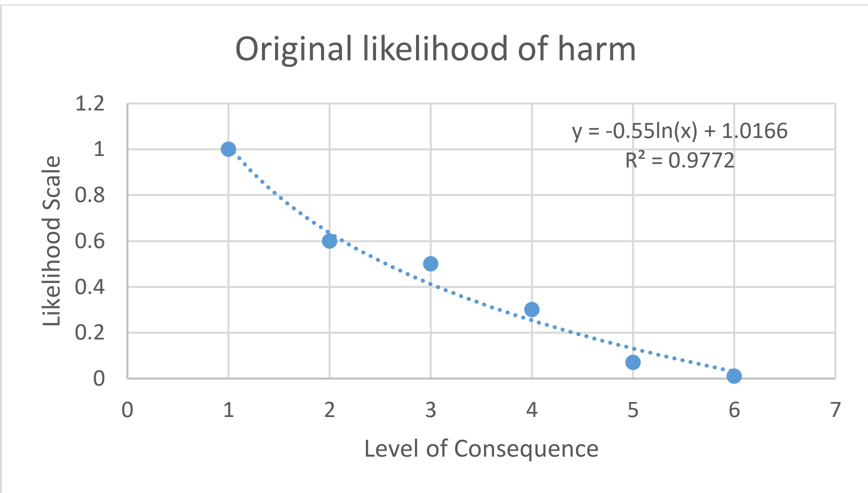

Figure 9.3: Original likelihood scale

While a linear fit would not be expected to be applicable, we expected that a logarithmic relationship may apply, on the assumption that the reduction of harm is slower than linear for the progression. This means that the effect of low WHODAS scores is given more importance than would be the case for a simple linear reduction.

A reversed likelihood scale was then developed with the following purpose in mind:

1. Needs to be broadly consistent with the findings from Chapter 5.
2. Needs to have improved logarithmic fit.
3. Needs to be numbers that are easy to calculate – this is so the method can be used by practitioners.

By trial and error the scale was determined, as shown in Figure 9.4.

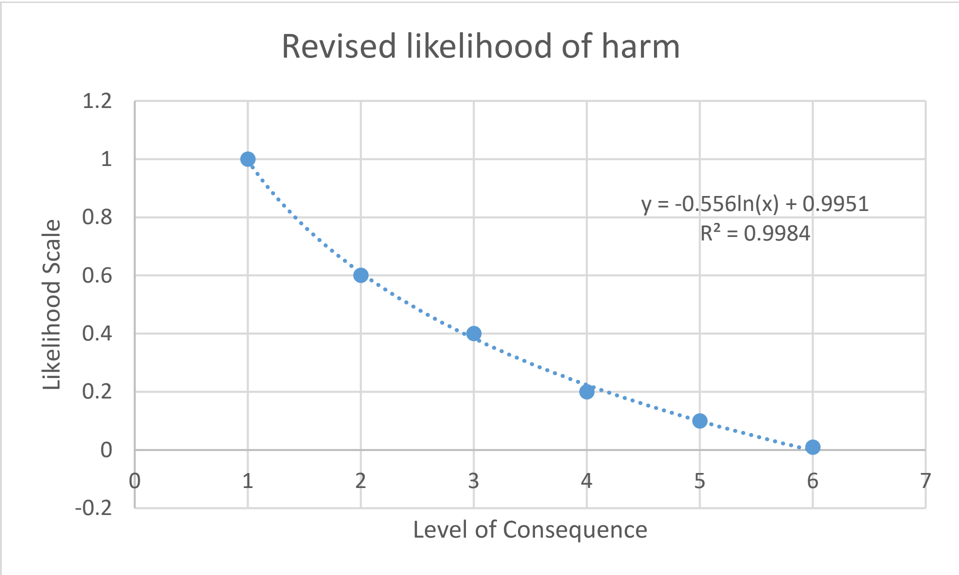

Figure 9.4: Revised likelihood of harm

Determining the WHODAS Consequence Thresholds

In designing this integration, the DQL thresholds and WHODAS scale were used from Chapter 5. The correspondence between these and the conventional consequence scale was determined based on Chapter 7. This was necessarily a subjective process, see Table 9.3.

WHODAS score	Description of the biological consequence
Multiple people affected and WHODAS up to 100	Health disaster, Multiple people affected.
WHODAS up to 100	Death, or whole-body paralysis.
WHODAS up to 60	Serious harm, e.g. leg paralysis.
WHODAS up to 30	Serious harm, amputation.
WHODAS up to 20	Moderate harm, hearing loss.
WHODAS up to 10	Minor harm, permanent but not debilitating musculoskeletal injury.
WHODAS up to 5	Minor harm, temporary effects.
WHODAS up to 2	No harm to human body.

Table 9.3: WHODAS categories

Integration of Consequences Scales for WHODAS and Conventional Safety Assessment

The WHODAS scores naturally range from 0 to 100. Hence, for compatibility, it was necessary to convert the conventional consequence scale to a 0 to 100 range. This is easily justified since most conventional scales in use are simple linear ones without strong justification of their own.

In combining the two, we also imposed the WHODAS categories shown in Table 9.3. We also integrated the NZ HSAW descriptors per [1]. Finally, while the WHODAS scale stops at 100, we added a further numerical value of 500 to accommodate health disasters where multiple people were affected with high WHODAS scores. The result is shown in Table 9.4.

Numerical value	500	100	60	30	20	10	5	2
Safety	Catastrophe: recovery systems inadequate, multiple deaths occur	Death	Serious harm: Incident results in permanent serious harm (notifiable injury),	Serious harm: Incident results in serious harm (notifiable injury)	Moderate incident: Incident occurs and exposure to serious harm	Minor harm. Incident occurs and minor harm	Incident without harm. Incident occurs with no harm	Hazard in control. Hazard present but existing controls prevent progression
Health	Health disaster: Multiple people affected with high WHODAS scores	WHODAS up to 100 (e.g. whole body paralysis)	WHODAS up to 60 (e.g. leg Paralysis)	WHODAS up to 30 (e.g. arm amputation)	WHODAS Up to 20 (e.g. hearing loss)	WHODAS up to 10 (e.g. permanent but not debilitating musculoskeletal injur)	WHODAS Up to 5 (e.g. temporary effects)	WHODAS up to 2 No harm to human body.

Table 9.4: Descriptions for each level of consequence

Integration into a New Risk Matrix with Decision Thresholds

Finally, these various improvements were put together to create a new risk matrix, one that accommodates both safety and health, see Figure 9.5.

The colour allocation is explained as follows – these become the decision thresholds for the new method. According to the previous version of DQL thresholds in Chapter 5, the reversed DQL thresholds was then determined. The correspondence between DQL and conventional risk was indicated in Table 9.5.

Qualitative estimate	***Likelihood of harm***								
Almost certain	***10***	5000	1000	600	300	200	100	50	20
Likely	***6***	3000	600	360	180	120	60	30	12
Possible	***4***	2000	400	240	120	80	40	20	8
Unlikely	***2***	1000	200	120	60	40	20	10	4
Rare	***1***	500	100	60	30	20	10	5	2
Almost incredible	***0.1***	50	10	6	3	2	1	0.5	0.2
Severity of harm (Consequence) hierarchy	Numerical value	500	100	60	30	20	10	5	2
	Safety	Catastrophe: recovery systems inadequate, multiple deaths occur	Death	Serious harm: Incident results in permanent serious harm (notifiable injury),	Serious harm: Incident results in serious harm (notifiable injury)	Moderate incident: Incident occurs and exposure to serious harm	Minor harm. Incident occurs and minor harm	Incident without harm. Incident occurs with no harm	Hazard in control. Hazard present but existing controls prevent progression
	Health	Health disaster: Multiple people affected with high WHODAS scores	WHODAS up to 100 (e.g. whole body paralysis)	WHODAS up to 60 (e.g. leg Paralysis)	WHODAS up to 30 (e.g. arm amputation)	WHODAS Up to 20 (e.g. hearing loss)	WHODAS up to 10 (e.g. permanent but not debilitating musculoskeletal injury)	WHODAS Up to 5 (e.g. temporary effects)	WHODAS up to 2 No harm to human body.

Figure 9.5: The proposed new risk matrix integrating long-term health into the risk assessment method.

DQL (C x L)	Colour in risk map	Description	Principle of Action.	Authority for continued operation	Reporting
1000+	Grey	Cessation.	Interruption must be undertaken at this point of time. Ensure preventions and recoveries are sufficient and can effectively manage the risk in the future operations.	Board	CEO to advise Board as soon as practicable.
120+ to 1000	Purple	Unacceptable risk.	Operations to cease until risk reduction is achieved. Ensure provenance of Disaster Recovery mechanisms in addition to Preventative means.	Board	CEO to advise Board as soon as practicable.
60+ to 120	Red	Urgent treatment.	Urgent implementation of treatment required. Operations proceed with caution and ongoing monitoring of risk	CEO	Technical manager to advise CEO as soon as practicable, and report regularly on status of the risk and its treatment.
10+ to 60	Yellow	Consider treatment.	Implement treatment in a reasonable time period. Operations proceed, with monitoring to detect if risk becomes worse or persistent	Technical manager	Team leader to report periodically to Technical manager on the risk and the progress of the treatment plan.
0 to 10	Green	No intervention necessary.	No further treatment required. Operations continue, with ongoing monitoring to check the efficacy of existing controls/barriers/procedures. Conduct periodic (e.g. annual) re-assessment of the risk.	Team leader	Staff to report periodically to Team leader on the state of this risk.

Table 9.5: Integrated scoring method that accommodates both DQL and conventional risk assessment methods

9.3 Application of Integrated H&S Risk Assessment to Case Study

This integrated methodology was then applied to the potato topping operations. The conventional safety assessment is shown in Table 9.6.

Specific Hazard	Consequence (C), as per 'Severity of harm' scale	Likelihood (L) of that consequence arising	Risk (C x L)	Action required
Repetitive operations	3	6	18	Urgent treatment
Noise – Hearing loss	3	3	9	Consider treatment
Electrocution	5	2	10	Consider treatment
Worker entrapped in conveyor	5	3	15	Consider treatment

Table 9.6: Conventional risk assessment for potato topping operations

When the new integrated method was applied, the results were as shown in Table 9.7. While the numbers are different – because the scales have changed – the outcomes are the same, as evident in the 'Action required' field.

Specific hazard	Consequence (C), as per 'Severity of harm' scale	Normalised likelihood of harm (L)	DQL Risk (C x L)	Action required
Inhale dust - lung disease	2	1	2	No further treatment required.
Electrocution	30	1	30	Consider treatment
Impact damage	10	1	10	No further treatment required.
Noise - hearing loss	10	2	20	Consider treatment
Repetitive operations – debilitating musculoskeletal injury	10	6	60	Urgent treatment
Temperature - Circulatory system diseases	10	0.1	1	No further treatment required.
Tips, slips and falls	10	2	20	Consider treatment
Uncomfortable working positions – debilitating musculoskeletal injury	10	2	20	Consider treatment
Worker entrapped in conveyor – figure jammed or amputation	30	1	30	Consider treatment

Table 9.7: DQL risk assessment for potato topping operations

9.4 Discussion of the Integrated H&S Risk Assessment Method

Compared with conventional risk assessment, the DQL method encourages a greater emphasis on health, and therefore anticipates hazards such as dust, uncomfortable working positions, noise, trips, etc., that were not included in the conventional assessment which tends to be more alert towards accidents. Combining both methods allows for a more comprehensive analysis.

We propose that the two methods are complementary and with different objectives. In both DQL and conventional risk assessment, the results are numerical outcomes, which can usefully contribute to health and safety management.

We suggest DQL should be applied to the conventional risk assessment in parallel, as an assistant to measure the long-term harm and also as part of the continuous improvement process. It specially contributes to identifying the non-obvious and long-term health issues and their corresponding consequences. For identifying the likelihood of a long-term health hazard, DQL can assist in determining the likelihood using 'frequency of a single incident arising' and 'likelihood of consequence arising'. A potential work stream integrating DQL and conventional risk assessment was developed, see Figure 9.6.

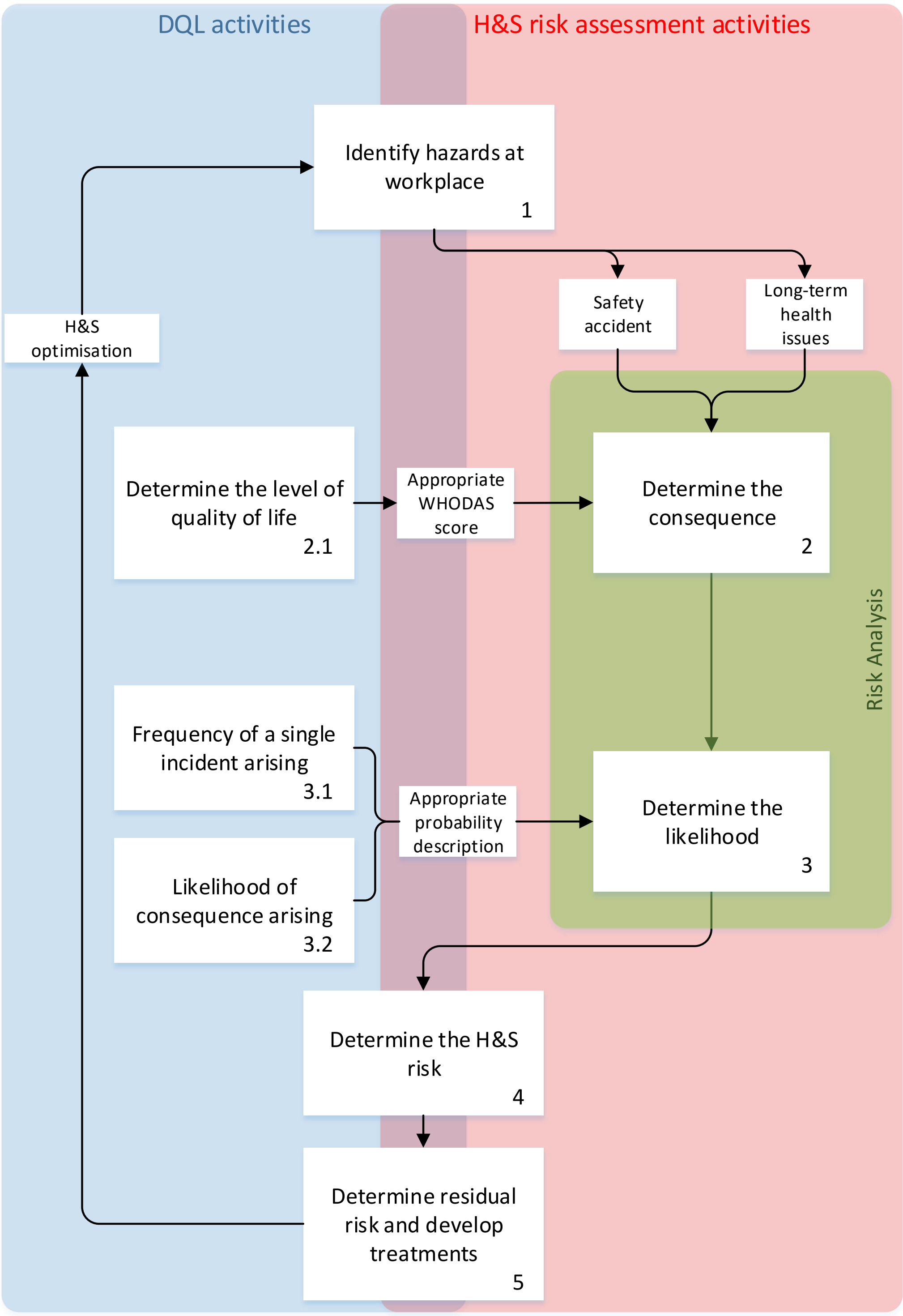

Figure 9.6: The integration work stream

Chapter 10: Discussion

10.1 Implications for Practitioners

'RASH' Model

The model is particularly focused on the health and chronic harm component of H&S, as opposed to the accident or safety part. This is deliberate, because the chronic harm part is under-represented in the safety literature compared to the safety part. It is much easier in industry to address the safety part, because the consequences of an accident are immediately apparent. Many of the safety systems are built on that assumption of immediacy, e.g. accident and near-miss reporting systems. Consequently, the continuous improvement processes work quickly and effectively for safety, but only weakly for long-term harm. This work makes a contribution by proposing a set of mental processes in the mind of the worker at the moment before the harm occurs. By framing these in terms of standard psychological constructs (many of which have their own measurement instruments), it is hoped that future work may lead to a situation where workers can be trained to put aside these perverse antecedents and thereby avoid chronic harm.

Diminished Quality of Life

Health issues are under-represented in the safety literature compared to accidents, hence, there is a need to develop an instrument to manage both health and safety. It is much easier for industry people to manage safety because an accident tends to have immediate consequences. By contrast, health problems are difficult to identify in the workplace, and some of the health problems require a period to occur or cumulative exposure. The DQL instrument presented here is focused on hazards and their biological consequences in the manufacturing industry. For its implementation, the methodology requires input from a number of industry professionals, such as an engineering technologist, H&S, and occupational hygienist/therapist. In principle, the methodology is applicable to other areas, such as construction, chemical and process engineering, agriculture, etc.

The Integration of OHS Risk and Plant Simulation

A quantitative methodology has been developed for managing OHS risk and production economics. Plant simulation was used to measure the risk at each working process through a DQL routine, which provides a way to manage OHS risk simultaneously. Researchers from other industries, such as construction, chemistry, forestry and agriculture, could also find application for using this methodology.

Development of an integrated methodology for health and safety risk assessment

A quantitative methodology has been developed for assessing health and safety risks. Compared with conventional risk assessment, the DQL method encourages a greater emphasis on health. We propose that the two methods are complementary with different objectives. The result of the integrated risk assessment is numerical and has been modified in an easily-calculated version which is designed to be simple to apply.

Integrating DQL with conventional risk assessment
The DQL has a special focus on long-term health risk measurement. This integration allows people to use the conventional assessment methodology to measure long-term health risks. We suggest that this methodology can also be employed as part of the continuous improvement process in OHS. It especially contributes to identifying non-obvious and long-term health issues and their corresponding consequences. In principle, this method can be applied to multiple industries.

10.2 Limitations

The method has some limitations:

- The 'RASH' model and 'perverse agency' is conceptual in nature, and the proposed causality is thus speculative. We have designed the model to improve the robustness, by including extant concepts from psychology where possible. However, this does not guarantee that the model is correct. Another limitation of the 'RASH' model is that we have designed the model from a pejorative perspective, i.e. of the worker who is taking a safety shortcut. There are many other workers who do not behave in this way, and the model does not represent their actions.
- Subjective judgement of the frequency and likelihood of DQL methodology is one of the limitations. This is common to most risk management methods. To solve this problem, qualitative research may be helpful to assess a person's subjective judgement in safety concept description. However, this thesis aimed to develop a methodology to simultaneously manage OHS risk and production economics, hence the qualitative research was not applied here. Descriptions for frequency and likelihood were addressed to identify the deviation, see Chapter 5.3.6.
- Another limitation is that loops of causality have not been included in the DQL methodology. Some factors (such as lighting and noise) cause fatigue, which may reduce concentration and increase the risk of accidents.
- This thesis has used representative data to evaluate WHODAS scores. It could be interesting to see the variability between workers (and possibly across different cultures) to the WHODAS scores.
- The methodology developed by the integration requires the user to have sound knowledge in plant modelling and simulation and OHS risk management (especially DQL methodology). Hence it could be a limitation when adopted to industry. A potential way to solve this limitation is to develop a DES and DQL based simulation software.

10.3 Future Research Opportunities

There are many opportunities for future research:

- The conceptual model RASH provides a broad framework within which are numerous implied relationships of causality. Future work could be directed to verify whether the sub-processes do actually work as depicted, and what the conditional factors (contingency variables) might be.

- Future work associated with simulation is that it could involve *time* as an attribute in safety and simulation methodology. This is currently limited by the inadequate literature on health consequences and time aspects. For example, some health consequences (e.g. hearing loss) can be cumulative, and difficult to detect the exposure time duration. The current DQL methodology is developed based on subjective judgment of the *frequency of the incident arising* for a reasonable working duration. This might be improved by future research which focuses on the long-term evolution of occupation health consequences.
- Crew Resource Management (CRM) is largely used in airline crew communication where human error can result in fatal consequences. CRM is primarily focused on safety improvement with considerations of decision making, physiological conditions, and situation awareness. Applications of high-risk environment were found [359] [360] [361]. Alternatively, many manufacturing accidents are caused by human error [107], hence, future work associated with CRM and H&S risk in manufacturing industry could be valuable.
- Perverse agency (PA) is a new concept presented by this work. PA refers to "application of poor judgement whereby the protagonist persists (by showing decisiveness, action, and commitment) with an unwise course of action and willing assumption (personal acceptance) of risk that others would consider unreasonable, to achieve what they feel is a good objective" [107]. However, this conceptual work has not been validated yet. The future work associated with PA could be the validation and application.
- Future project associated with ontology could be interesting. An ontology study would need more computer sciences input to process the mathematical relations. Quantitative elements, e.g. event tree, could be valuable to include.
- A future study could focus on tightly integrating DQL with plant simulation software. This would require access to source code. The present method does the DQL analysis in a separate spreadsheet, and it would be helpful for the user if a user-friendly interface were available.
- Applications in other industries. We have already applied our methodology to some manufacturing industry cases, e.g. engineering workshop and a food industry (bakery). There is a potential to apply DQL and simulation to the other industries for example, construction, forestry and agriculture.
- SME growth of H&S, environment management, and production economics can be valuable future research. An integration of H&S risk and production economics has been delivered by this work and with a special focus on the SMEs. SMEs need to grow productivity, which requires capital investment and changes to the structure of their operational systems. Chapter 8 has potential to assist with growth decisions, specifically in the complex investment mix of hardware and labour, and the concomitant effect of operations on H&S. Environmental integrities for manufacturing

operations are associated with pollution, waste, and toxicity. These emissions could be managed using risk methodologies, hence further could be measured using DQL.

Chapter 11: Conclusions

11.1 Summary

The original objectives of the project were to develop a methodology to manage OHS risk alongside engineering economics. Conceptual models of "RASH" and "Perverse Agency" were developed to analyse the risk-taking activities of workers. A DQL methodology was developed to assist in measuring long-term health risks. The methodology was then integrated with plant simulation for consideration alongside engineering economic parameters. The methodology was applied to two case studies: simple system (engineering workshop) and complex system (food production). DQL was then integrated with conventional risk assessment to build a mechanism to measure non-obvious injuries and chronic health issues using the conventional methods.

11.2 Novel Contributions

The thesis presents several novel contributions:

- An instrument named "Diminished Quality of Life" was developed to measure the risk of H&S, which is especially focused on long-term effects. This is achieved by adapting the established World Health Organisation Disability Assessment Schedule (WHODAS) quality of life score to workplace health. Specifically, the method is used to identify the likelihood of an exposure incident arising (as estimated by engineering technologists and H&S officers), followed by evaluation of the biological harm consequences. Those consequences are then scored by using the WHODAS 12-item inventory. The result is an assessment of the DQL associated with a workplace hazard. This may then be used to manage the minimisation of harm, exposure monitoring, and the design of safe systems of work.
- A new concept of hazard at work has been presented named "Perverse Agency". We define Perverse Agency as "application of poor judgement whereby the protagonist persists (by showing decisiveness, action, and commitment) with an unwise course of action and willing assumption (personal acceptance) of risk that others would consider unreasonable, to achieve what they feel is a good objective" [107]. This idea is potentially applicable to many different areas of human decision-making.
- A conceptual model named "RASH" was developed in this thesis. RASH offers a finer-resolution explanation of risk-taking activities in the organisational context. It explains the causality whereby people compromise their personal occupational health and safety. It does this by combining new and old concepts. It incorporates several well-established elements of psychology; namely motivation theory, personality, worldviews, self-efficacy, locus of control, dark triad, and ethics. It also uses the concept of organisational alignment, which is from strategic human resource management (SHRM) and organisational behaviour (OB) more generally.
- An integrated risk assessment has been developed, this is based on DQL methodology and conventional risk assessment. The integration particularly contribute to manage long-term health risk. A new risk matrix with decision thresholds was also developed.

- Production economics has been considered in the thesis as a novel way to optimise the performance of a manufacturing system, for the unusual class of situations where the product moving through the simulation is not merely a physical product, as in conventional simulation approaches, but rather the combination of people (students) and their partially completed physical product.
- A new system-based methodology has been developed to integrate safety risk with plant simulation. The methodology involves DQL routines which are created within plant simulation, thereby enabling the safety risk of each activity to be determined. Long-term health risks are included in the methodology. This system-based methodology allows for safety risk to be considered along with plant economics.
- This thesis has the potential to assist with SME growth decisions, specifically in the complex investment mix of hardware and labour, and the concomitant effect of operations on societal outcomes as measured in H&S. The methodology presented here is an integration of DQL and plant simulation, which provides a novel way to manage economic outcomes and OHS. We especially focused on small and medium enterprises in the manufacturing industry.
- An integration of DQL and conventional risk assessment. This allows people to use conventional risk assessment to measure long-term health risks. We achieved this by developing a new risk matrix, consequence and likelihood thresholds and corresponding response activities for different level of risk.

11.3 Overall Conclusion

The purpose of the thesis was to develop a quantitative methodology to manage occupational health and safety, and simultaneously optimise production economics via plant simulation methodology. Presenting OHS risk via a quantitative and virtualised simulation model contributes positively to risk management, especially dealing with residual risk. Long-term health risks have also been considered in this thesis, and this is managed by the DQL methodology. Methodologies that have been applied to this thesis include: OHS risk management, quality of life, decision making, ontology, process , computational modelling, discrete event simulation, and Monte Carlo sampling.

The following major results are obtained:

- A conceptual physiological model was developed to address why workers take risky decisions in the workplace. A new concept, namely *perverse agency,* presented.
- The DQL risk management methodology has been developed to use quantitative methods to measure OHS risk in the workplace. DQL has a specific focus on long-term health effects (chronic health).
- A methodology integrating DQL with conventional risk assessment was developed. Compared with the conventional methodology, the integration methodology is complementary with different objectives (has a special focus on long-term health effects).
- Integrating DQL risk management with plant simulation. This is achieved via discrete event simulation. The DQL routine was programmed to measure OHS risk in the

simulation. This methodology has been applied to an engineering workshop and a bakery industry.

- A particularly focus on SME growth. A method of integrating OHS risk management and production economics has been developed to help SME growth decisions.
- An integration of DQL and conventional risk assessment. This work allows people to use conventional risk assessment to measure long-term health risks.

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Appendix A: Publications

Publication 01:

Ji, Z., Pons, D., Pearse, J. Why Do Workers Take Safety Risks?—A Conceptual Model for the Motivation Underpinning Perverse Agency. *Safety* 2018, *4*, 24. https://doi.org/10.3390/safety4020024

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Please indicate the chapter/section/pages of this thesis that are extracted from co-authored work and provide details of the publication or submission from the extract comes:

Ji, Z., Pons, D., & Pearse, J. (2018). Why Do Workers Take Safety Risks?—A Conceptual Model for the Motivation Underpinning Perverse Agency. *Safety, 4*(2), 24. https://doi.org/10.3390/safety4020024

Please detail the nature and extent (%) of contribution by the candidate:

Author Contributions: S.J. and D.P. created the RASH model and concept. All authors contributed to the refinement of the model and the writing of the paper. D.P. and J.P. provided project direction and supervision.

Candidate's contributions:
Model creation 65%
Writing paper first draft: 85%
Editing paper: 65%

Certification by Co-authors:
If there is more than one co-author then a single co-author can sign on behalf of all
The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work
- In cases where the candidate was the lead author of the co-authored work he or she wrote the text

Name: *Dirk Pons* Signature: *DJP* Date: *2 April 2019*

Publication 02:

Ji, Z., Pons, D., Pearse, J. Measuring Industrial Health Using a Diminished Quality of Life Instrument. Safety 2018, 4, 55. https://doi.org/10.3390/safety4040055

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Please indicate the chapter/section/pages of this thesis that are extracted from co-authored work and provide details of the publication or submission from the extract comes:

Ji, Z., Pons, D., and Pearse, J., *Measuring Industrial Health Using a Diminished Quality of Life Instrument.* Safety, 2018. **4**(4): p. 55 DOI: https://doi.org/10.3390/safety4040055

Please detail the nature and extent (%) of contribution by the candidate:

Author Contributions: S.J. and D.P. created the risk measuring instrument and concept. All authors contributed to the refinement of the model and the writing of the paper. D.P. and J.P. provided project direction and supervision.

Candidate's contributions:

Model/Instrument creation 70%

Writing paper first draft: 75%

Editing paper: 70%

Certification by Co-authors:

If there is more than one co-author then a single co-author can sign on behalf of all

The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work
- In cases where the candidate was the lead author of the co-authored work he or she wrote the text

Name: *Dirk Pons* Signature: *DJP* Date: *4 October 2019*

Publication 03:

Ji, Z., Pons, D., and Pearse, J., Plant system simulation for engineering trainingworkshops.Compu Appl Eng Educ. 2019; 1–14. https://doi.org/10.1002/cae.22171

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Please indicate the chapter/section/pages of this thesis that are extracted from co-authored work and provide details of the publication or submission from the extract comes:

Ji, Z., Pons, D., and Pearse, J., Plant system simulation for engineering training workshops. Computer Application in Engineering Education. 2019; 1–14. https://doi.org/10.1002/cae.22171

Please detail the nature and extent (%) of contribution by the candidate:

Author Contributions: S.J. and D.P. created the simulation model and optimisation plan. All authors contributed to the refinement of the model and the writing of the paper. D.P. and J.P. provided project direction and supervision.

Candidate's contributions:

Model/simulation programming 80%

Writing paper first draft: 75%

Editing paper: 70%

Certification by Co-authors:

If there is more than one co-author then a single co-author can sign on behalf of all

The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work
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Name: *Dirk Pons* Signature: *DJP* Date: *4 October 2019*

Appendix B: Diminished Quality of Life Instrument and WHODAS Instrument

DQL Instrument:

Operating the milling machine at engineering workshop.

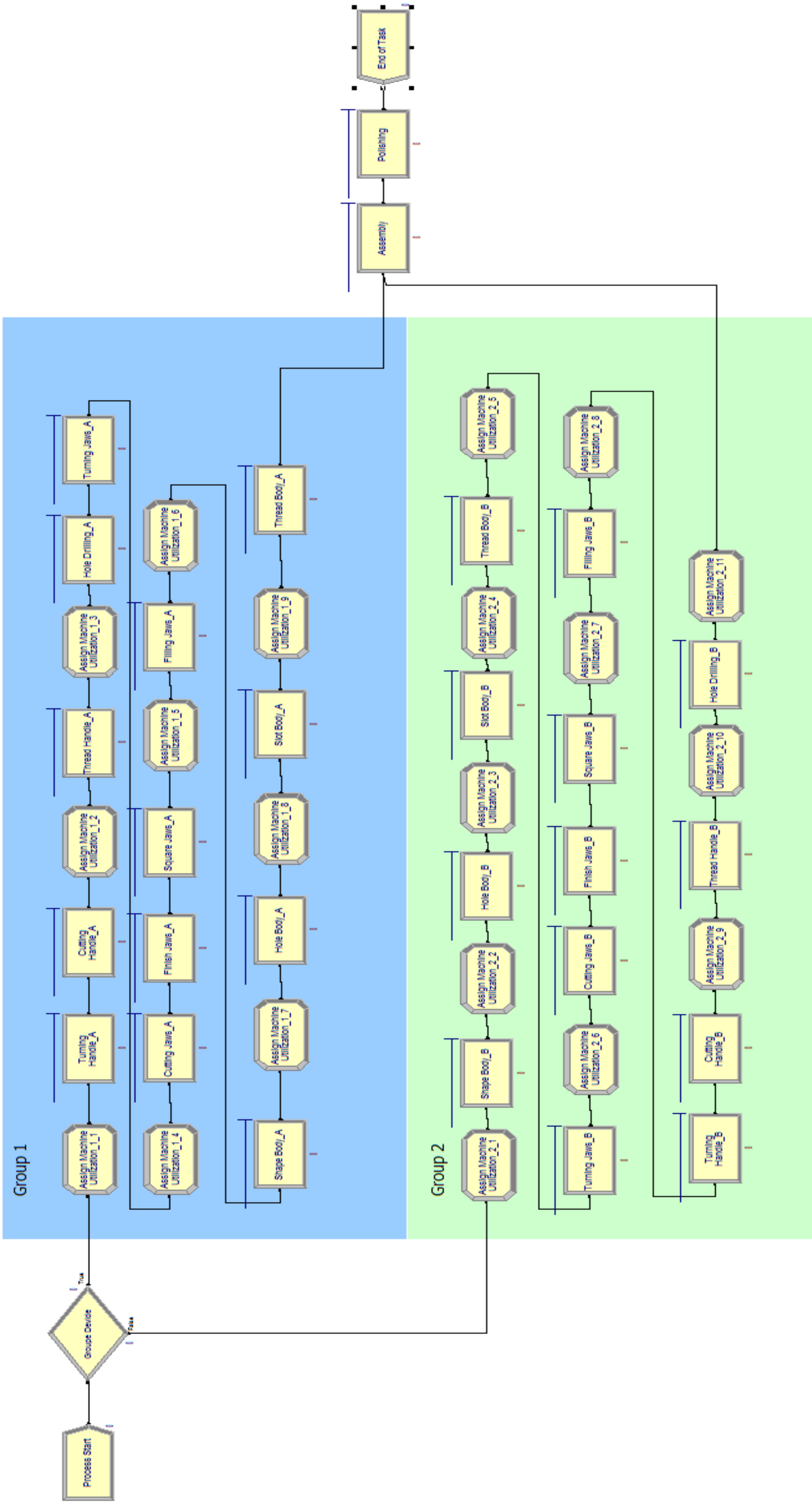
Diminished Quality of Life (DQL) Instrument							
A	B	C	D	E	F	G	H
Standard hazard categorisation, used as checklist by industry	*Severity Context is added by engineering technologist*	*Sub-category of column A per ontology*	*Estimate provided by engineering technologist or H&S officer*	*Sub-category of column C per ontology*	*Estimated by Occupational Hygienist or H&S officer*	*Derived from WHODAS*	*Computed (DxFxG)*
Hazards in Workplace	**Severity Context and current state**	**Incident Description** *(S: Safety Accident H: Health Issue)*	**Frequency of a single Incident arising in your working career at this site (Estimated for the workplace)**	**Biological Consequence**	**Likelihood of Consequence arising (Estimated for this workplace)**	**Consequence: Level of Harm (WHODAS)**	**Diminished quality of life (DQL)**
Chemical Exposure	Coolant and lubricating oil	H: Long term chemical exposure work environment	60%	Skin disease, e.g. dermatitis	50%	2.08	0.62
				Respiratory system compromise	30%	2.08	0.37
				Blood pressure compromise	7%	10.42	0.44
		S: Exposure to eye	30%	Eye injury	50%	12.50	1.88
		S: Exposure to skin	30%	Skin damage	50%	2.08	0.31
Cutting, Crushing and Squashing	Machine tools, open (not enclosed)	S: Accidentally injured by machine	50%	Amputation (arm, finger, foot, hand, and leg)	30%	47.92	7.19
				Lacerations	50%	14.58	3.65
				Bone injury	30%	17.92	2.69
				Death	7%	100.00	3.50
		S: Accidentally injured by hand tools	30%	Abrasion	50%	0.00	0.00
				Amputation (arm, finger, foot, hand, and leg)	7%	47.92	1.01
				Bone injury	30%	47.92	4.31
		S: Accidental bodily injury by foreign objects	50%	Lacerations	30%	14.58	2.19
		S: Accidental eye injury by foreign objects	30%	Eye injury	30%	64.58	5.81
Dust	Welding fumes with extraction system	H: Dust in lungs	7%	Respiratory system compromise	7%	2.08	0.01
Electrical Accident	Electrical mains voltage tools with RCD protection	S: Electrical burn	30%	Skin damage	30%	2.08	0.19
		H: Electrical shock	7%	Skin damage	50%	2.08	0.07
				Paralysis	50%	68.75	2.41
				Death	50%	100.00	3.50
Heat and Radiation	Welding, hot parts	S: Burn via fire, hot object, hot liquid, hot vapour	30%	Eye injure	30%	64.58	5.81
				Skin damage	50%	2.08	0.31
Impact Damage	Loose tools, falling parts, max. 10kg falling from 1 m. No moving vehicles	S: Workers hit by machine, forklift, and other objects	7%	Musculoskeletal injury	50%	2.08	0.07
				Abrasion	90%	0.00	0.00
				Bone injury	60%	47.92	2.01
				Lacerations	90%	14.58	0.92
				Skin damage	90%	2.08	0.13
				Paralysis	30%	68.75	1.44
				Death	30%	100.00	2.10
Lighting	Dated lighting fixtures	H: Uncomfortable, or strange light in workplace	7%	Eye fatigue	30%	12.50	0.26
Entrapment	PPE required in student workshop, work cloth provided, shoes potected by steel cap.	S: Get caught by machine	50%	Amputation (arm, finger, foot, hand, and leg)	30%	47.92	7.19
		S: Touch hot surface	30%	Skin damage	50%	2.08	0.31
		S: Trips, slips and falls	30%	Abrasion	60%	0.00	0.00
				Musculoskeletal injury	30%	2.08	0.19
				Lacerations	30%	14.58	1.31
				Eye Injury	7%	64.58	1.36
				Bone injury	7%	47.92	1.01
				Paralysis	7%	68.75	1.44
				Death	7%	100.00	2.10
Manual Heavy Loads and Repetitive Work	Maximum load 10kg	H: Moving heavy tools, machines and other objectives; or long-time repetitive work, e.g. packaging	30%	Muscle damage, tendon and ligament injury	30%	16.67	1.50
Noise	Occasional noise levels over 65 dB, ear plugs voluntary	H: Caused by machine operating	50%	Hearing loss	60%	12.50	3.75
Temperature	Reasonable temperature control	H: Uncomfortable temperature Environment	7%	Circulatory system diseases	50%	8.33	0.29
				Musculoskeletal injury	50%	16.67	0.58
Ventilation	Regular	H: Uncirculated air	7%	Respiratory system compromise	50%	2.08	0.07
Vibration	Occasional vibration caused by machine shake	H: Long term vibration exposure	50%	Muscle damage, tendon and ligament injury	30%	16.67	2.50
Uncomfortable Working Position	Possible bent neck when machine parts	H: Long term work in uncomfortable position	30%	Muscle damage, tendon and ligament injury	50%	16.67	2.50

Level of Biological Consequence - WHODAS:

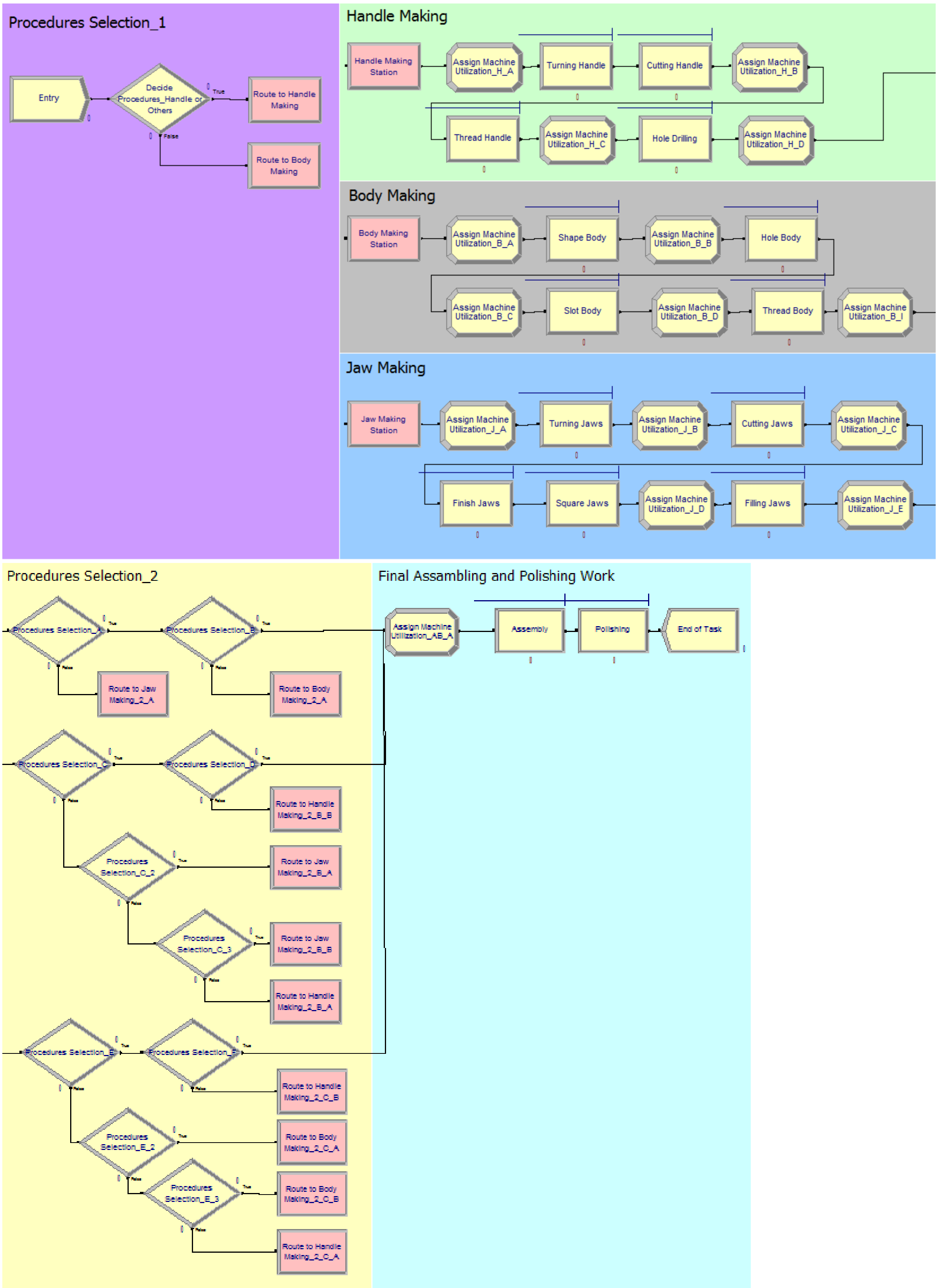
Question Number	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	
Hazard Description	Standing for long period, such as 30 minutes?	Taking care of your household responsibility?	Learning a new task, for example, how to get a new place?	How much of a problem did you have in joining in communitiy activities (for example, festivities, religious or other activities) in the same way as anyone else can?	How much have you been emontionally affected by your health problems?	Concentrating on doing something for tem minutes?	Walking a long distance such as a kilometre [or equivalent]?	Washing your whole body?	Getting dressed?	Dealing with people you do not know?	Maintaining a friendship?	Your day to day work/school?	Overall Score
Abrasion	0	0	0	0	0	0	0	0	0	0	0	0	0.00%
Amputation (Arm)	0	4	0	2	2	0	0	4	4	2	0	3	43.75%
Amputation (Finger)	0	1	0	0	1	0	0	1	1	1	0	1	12.50%
Amputation (Foot)	3	3	0	1	2	0	4	1	0	0	0	3	35.42%
Amputation (Hand)	0	4	0	1	2	0	0	4	4	2	0	3	41.67%
Amputation (Leg)	4	4	0	2	2	0	4	1	1	2	0	3	47.92%
Tendon and Ligament Injury	0	1	0	0	0	0	0	0	0	0	0	0	2.08%
Blood Pressure Problem	1	1	0	2	0	0	0	0	0	0	0	1	10.42%
Bruise to Soft Tissue	0	0	0	0	0	0	0	0	0	0	0	0	0.00%
Cardiovascular Disease	1	0	0	2	0	0	0	0	0	0	0	1	8.33%
Death	4	4	4	4	4	4	4	4	4	4	4	4	100.00%
Eye Injury	0	4	3	3	3	3	4	2	2	2	1	4	64.58%
Eye Fatigue	0	1	1	1	1	1	0	0	0	0	0	1	12.50%
Fracture	2	3	0	3	2	0	2	4	4	0	0	3	47.92%
Hearing Loss	0	0	1	1	1	0	0	0	0	1	0	2	12.50%
Lacerations	0	0	0	1	1	0	1	2	1	0	0	1	14.58%
Muscle Damage	2	2	0	0	1	0	1	1	0	0	0	1	16.67%
Musculoskeletal Disease	1	1	0	0	1	0	2	2	1	0	0	1	18.75%
Paralysis	4	4	0	4	3	0	4	4	4	2	0	4	68.75%
Respiratory System Problem	0	0	0	1	0	0	0	0	0	0	0	0	2.08%
Skin Damage, e.g.acid burn	0	0	0	0	1	0	0	0	0	0	0	0	2.08%
Skin Disease, e.g. dermatitis	0	0	0	0	1	0	0	0	0	0	0	0	2.08%
Tendon and Ligament Injury	1	1	0	0	0	0	1	0	0	0	0	1	8.33%

Appendix C: Simulation Programme

1. Simulation of the Engineering Workshop, the ‘status quo’.

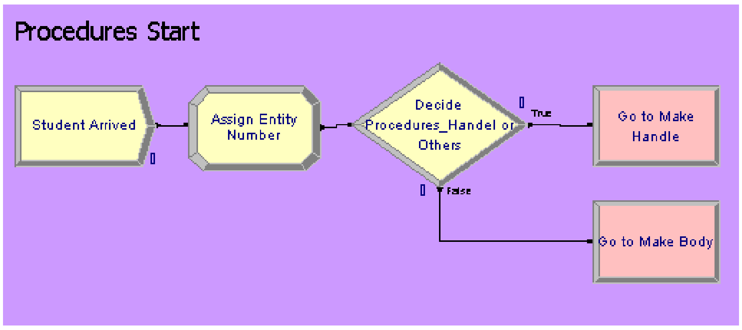


2. Simulation of the Engineering Workshop, the optimisation.

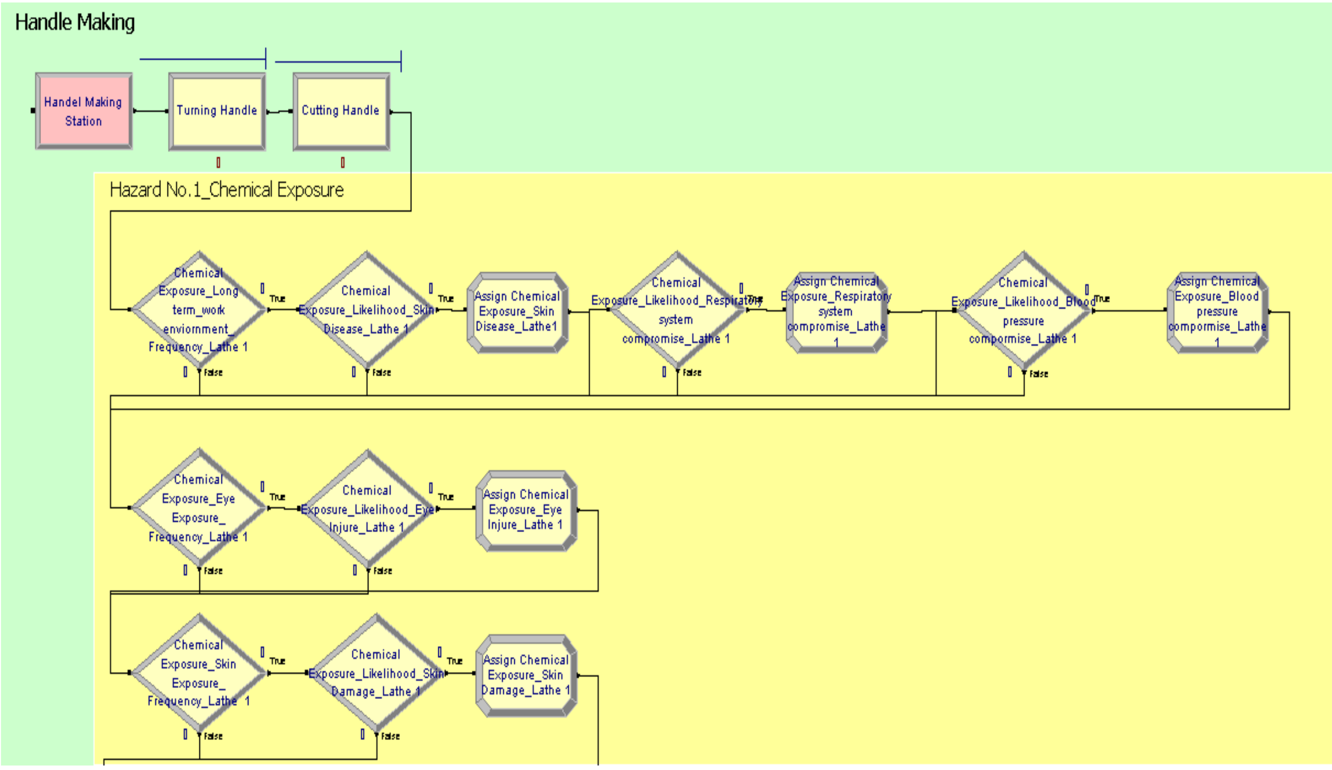


3. DQL Programming for the Engineering Workshop

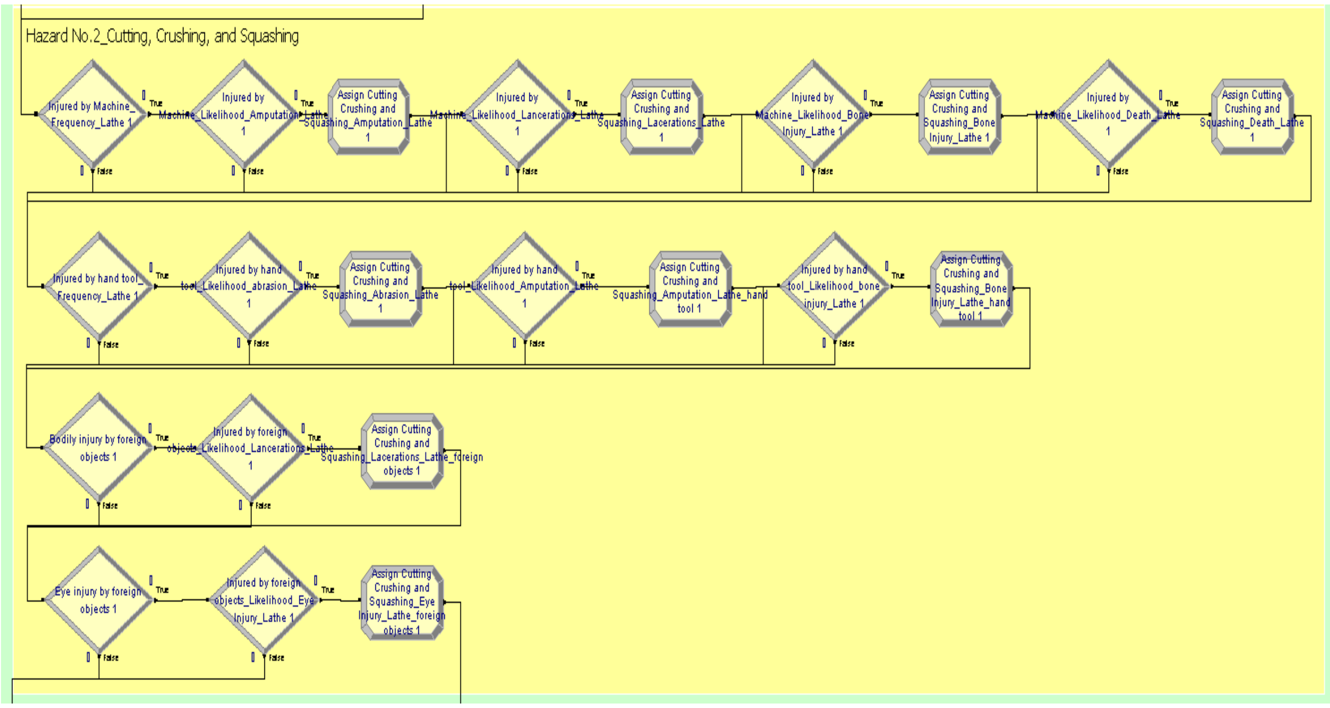
(1). Procedures Start



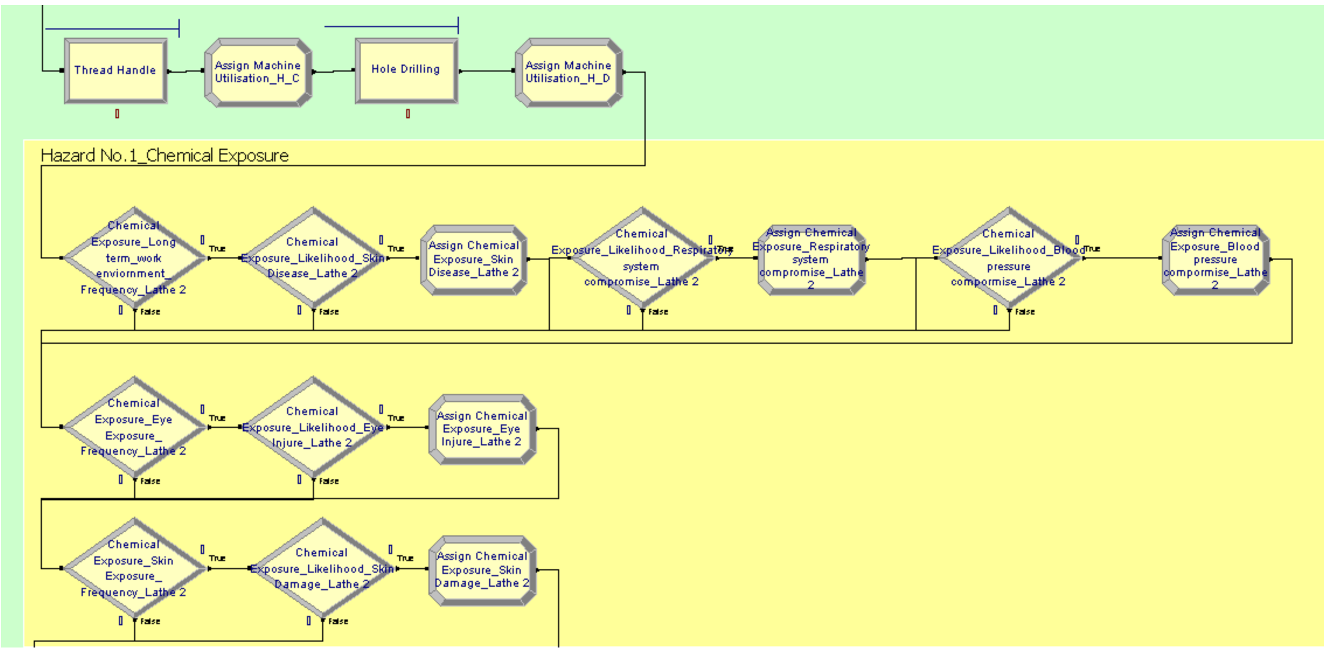
(2). Handle Making Part 1



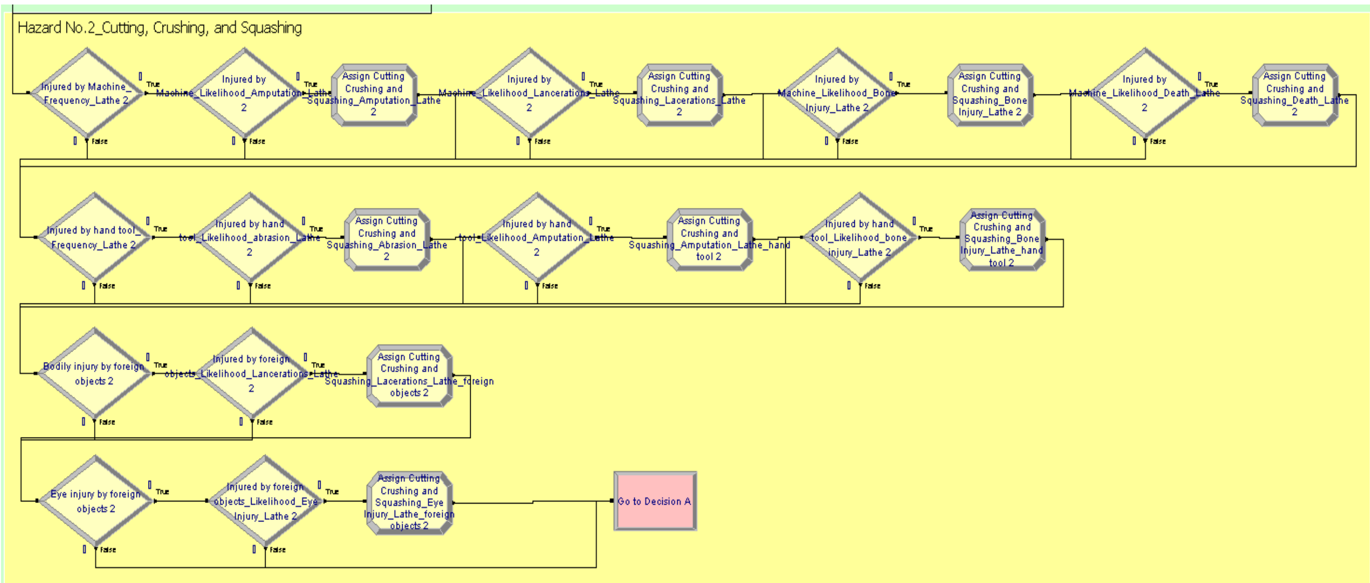
(3). Handle Making Part 2



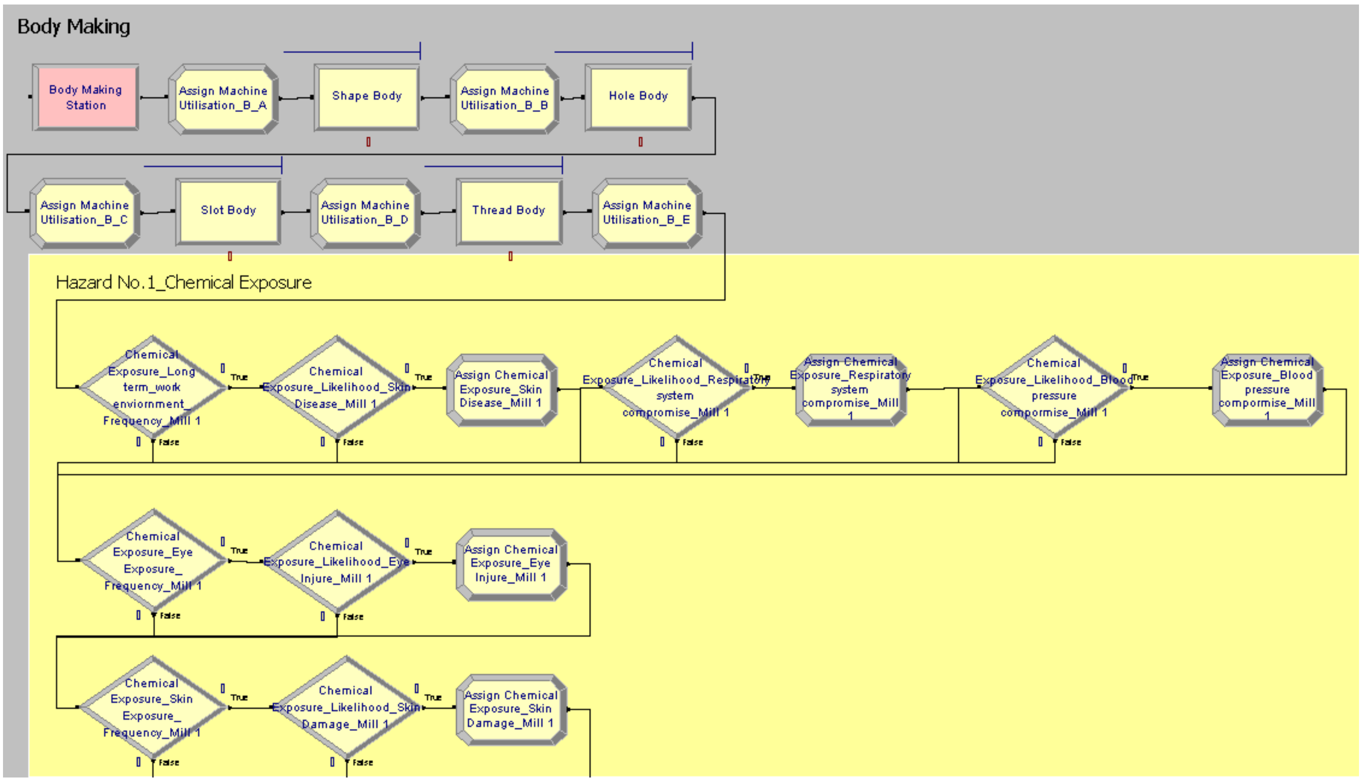
(4). Handle Making Part 3



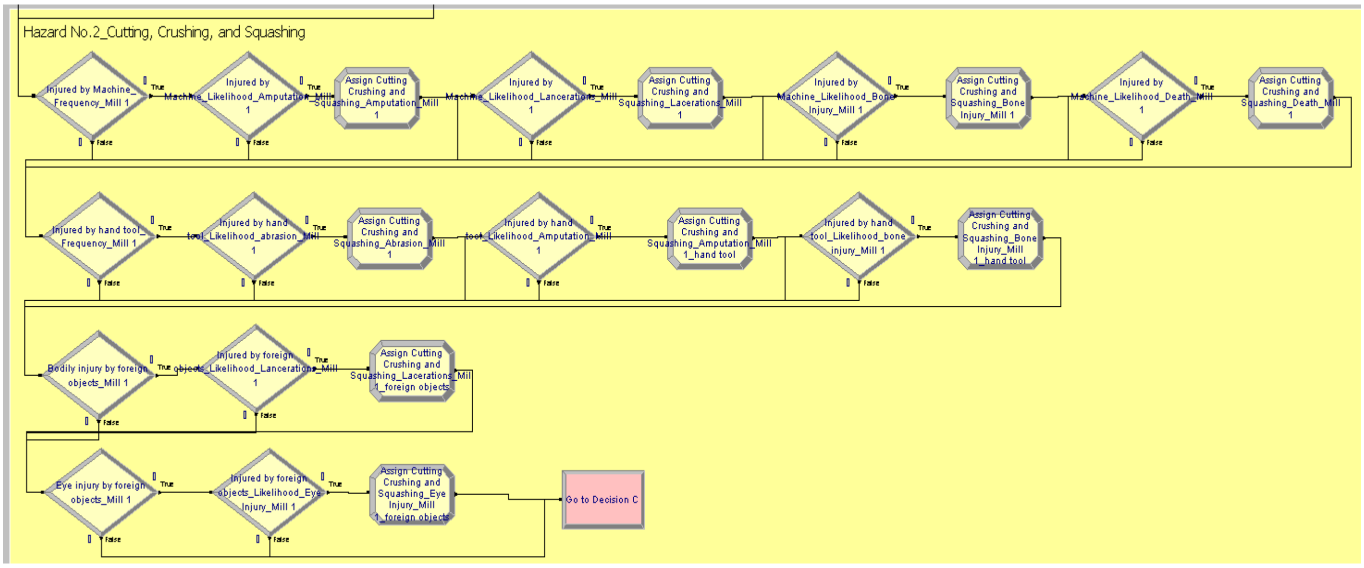
(5). Handle Making Part 4



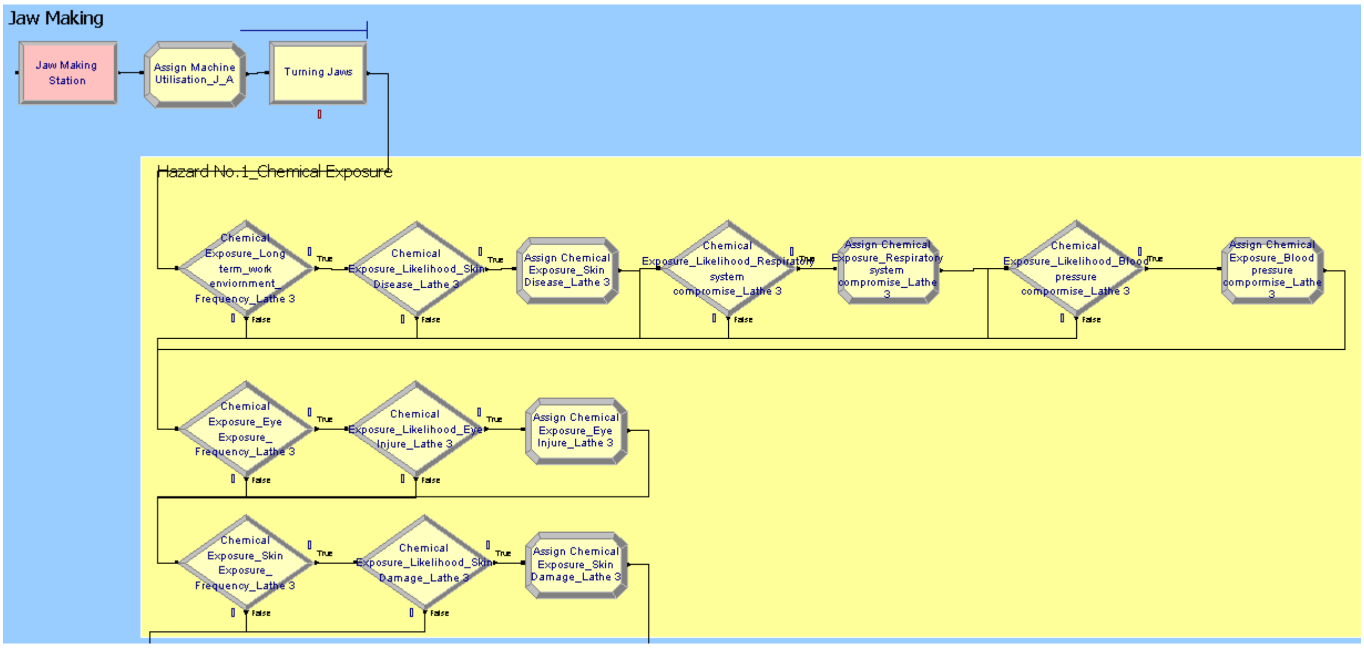
(6). Body Making Part 1



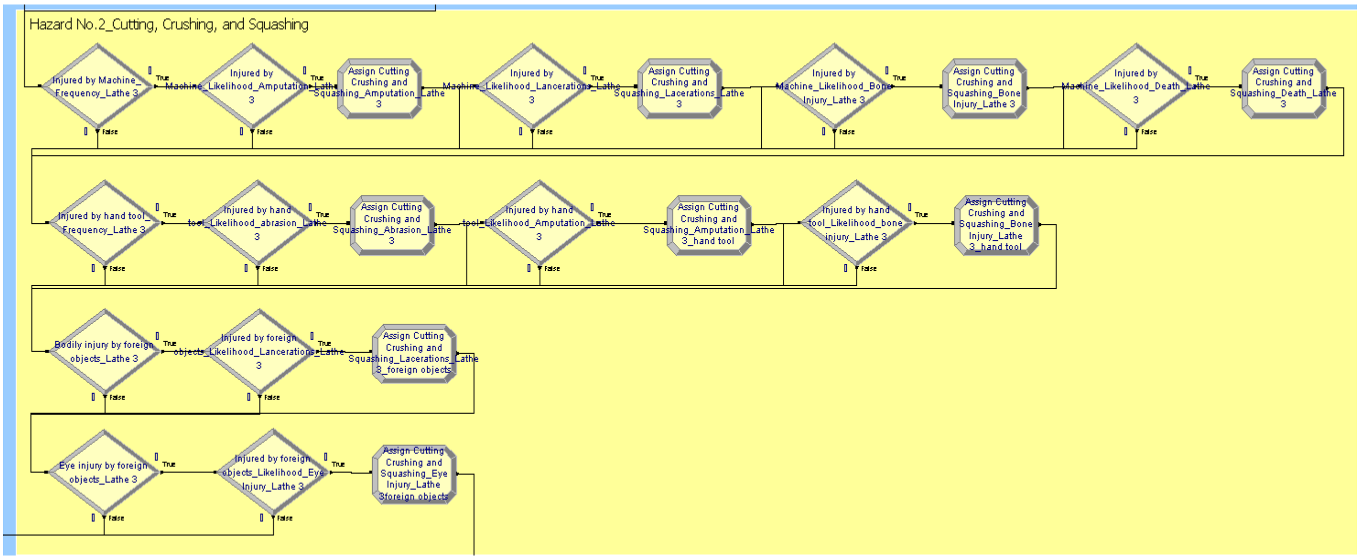
(7). Body Making Part 2



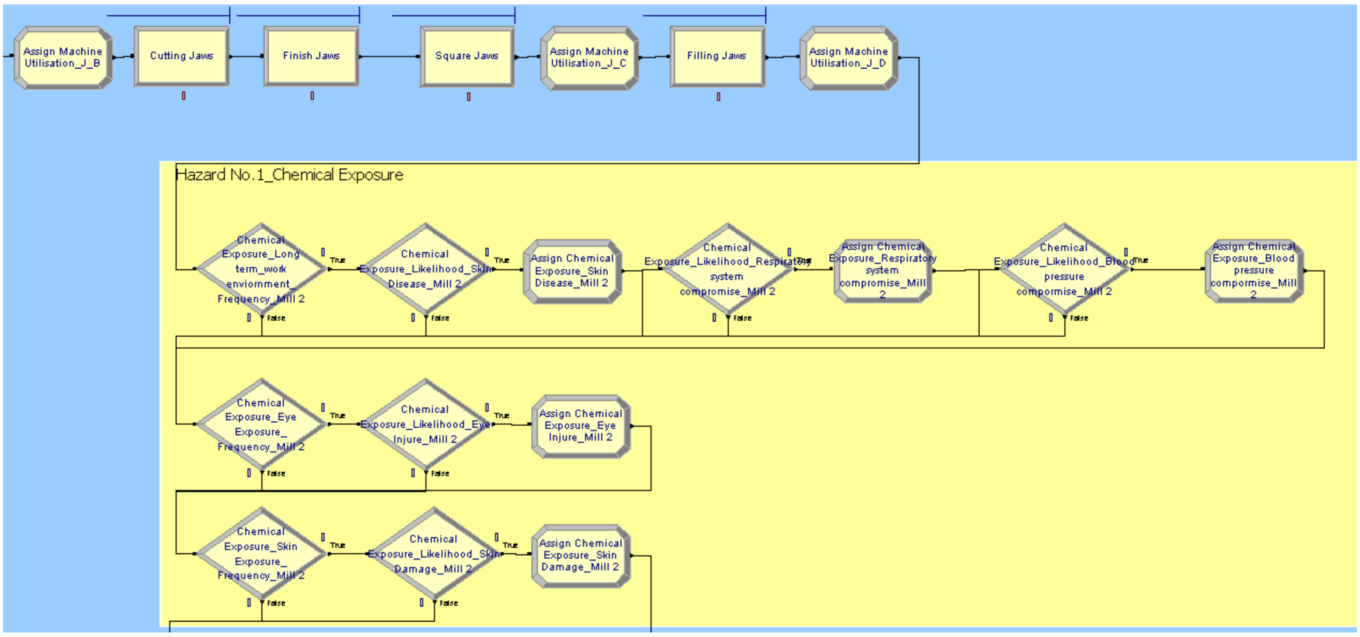
(8). Jaw Making Part 1



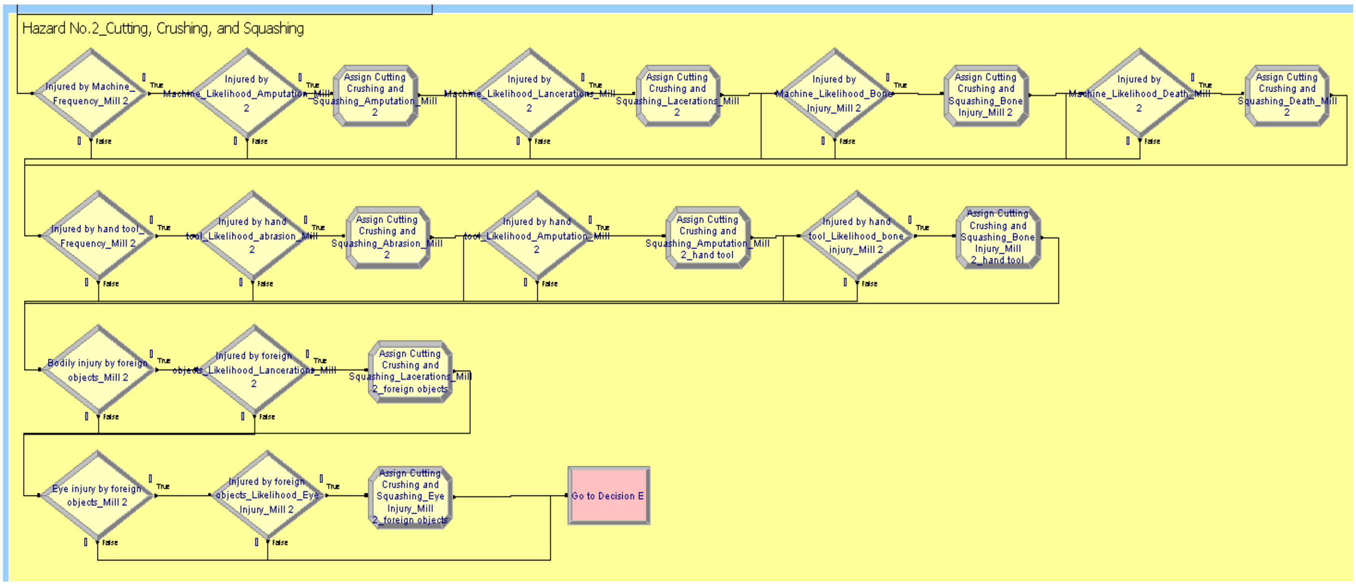
(9). Jaw Making Part 2



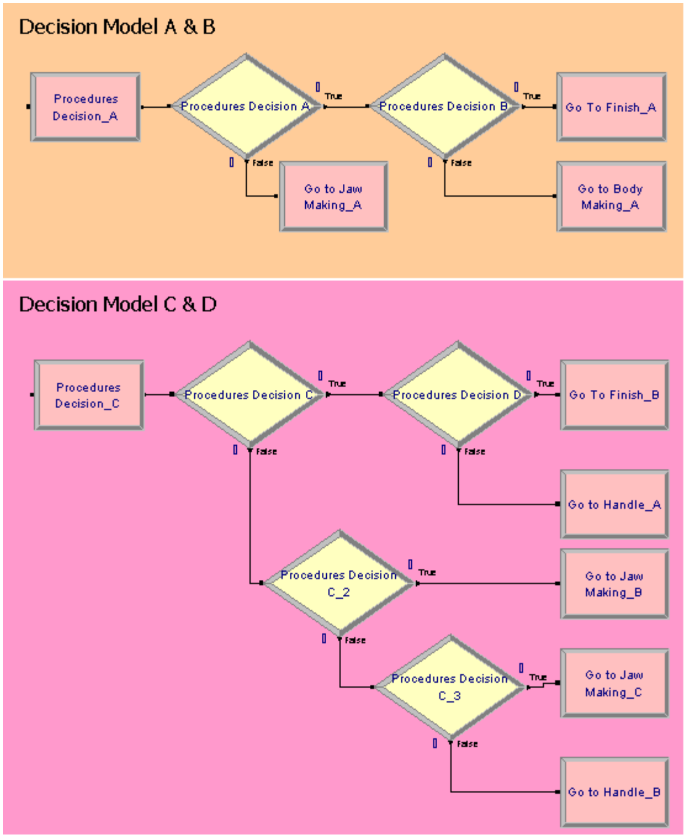
(10). Jaw Making Part 3



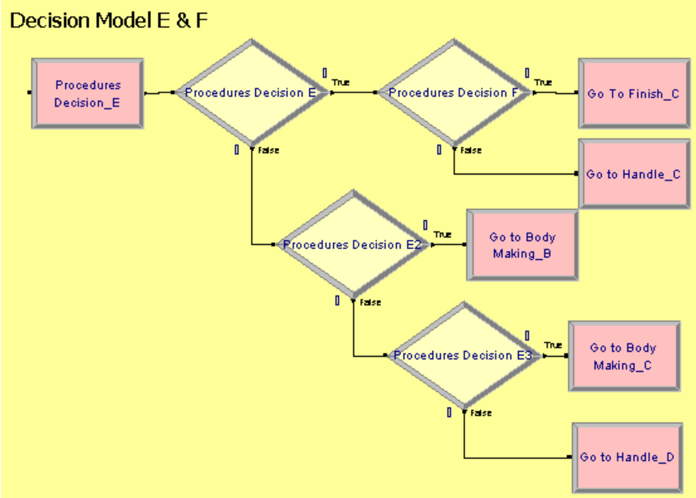
(11). Jaw Making Part 3



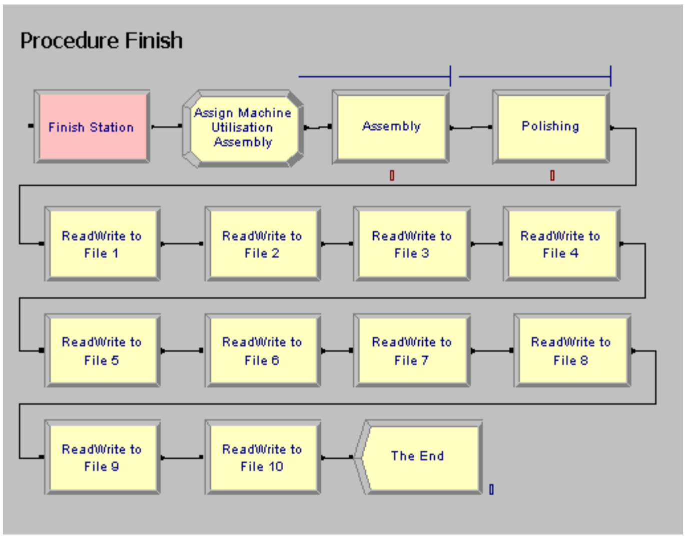
(12). Decision Model Part 1



(13). Decision Model Part 2

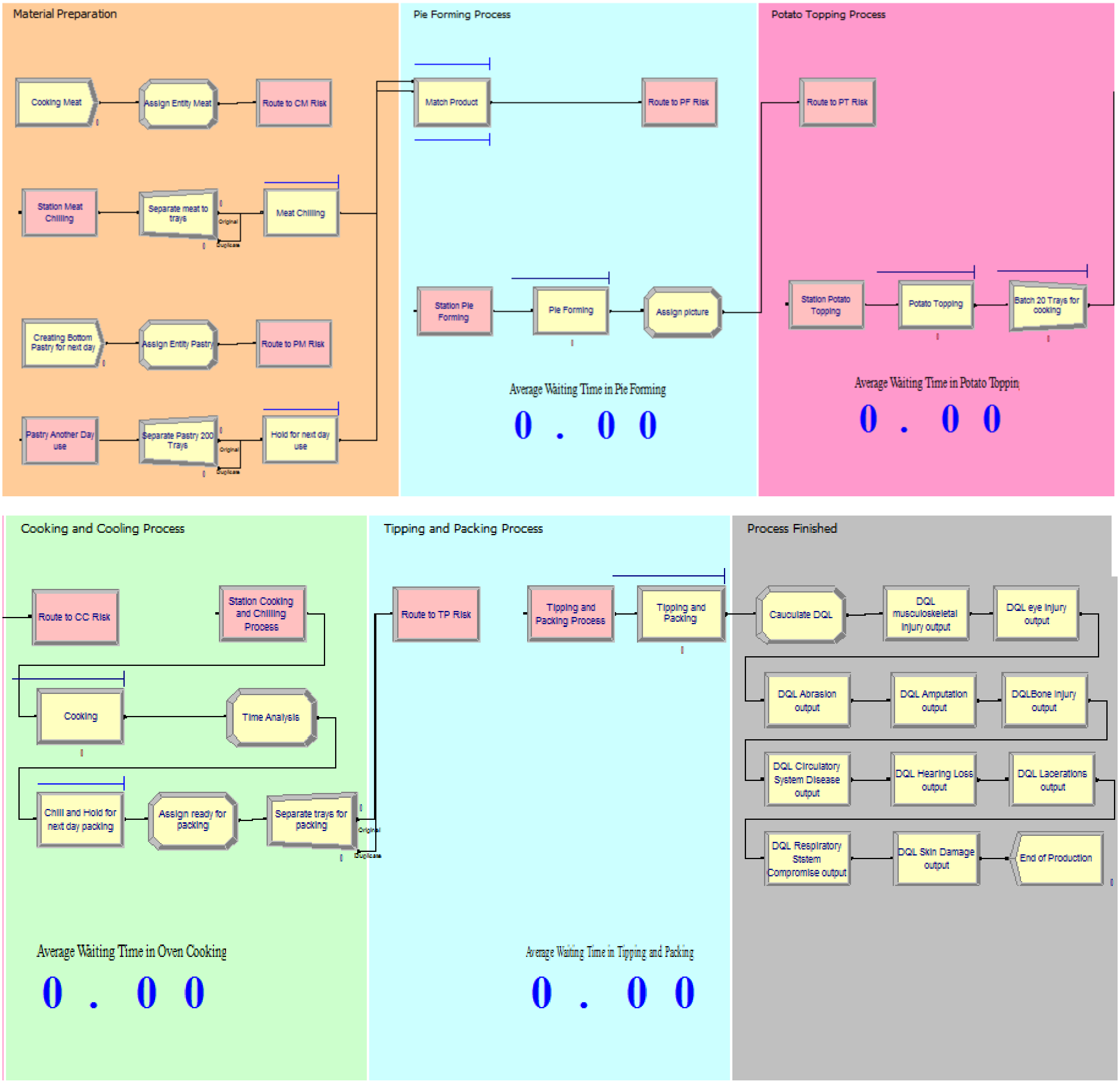


(14). Final Process

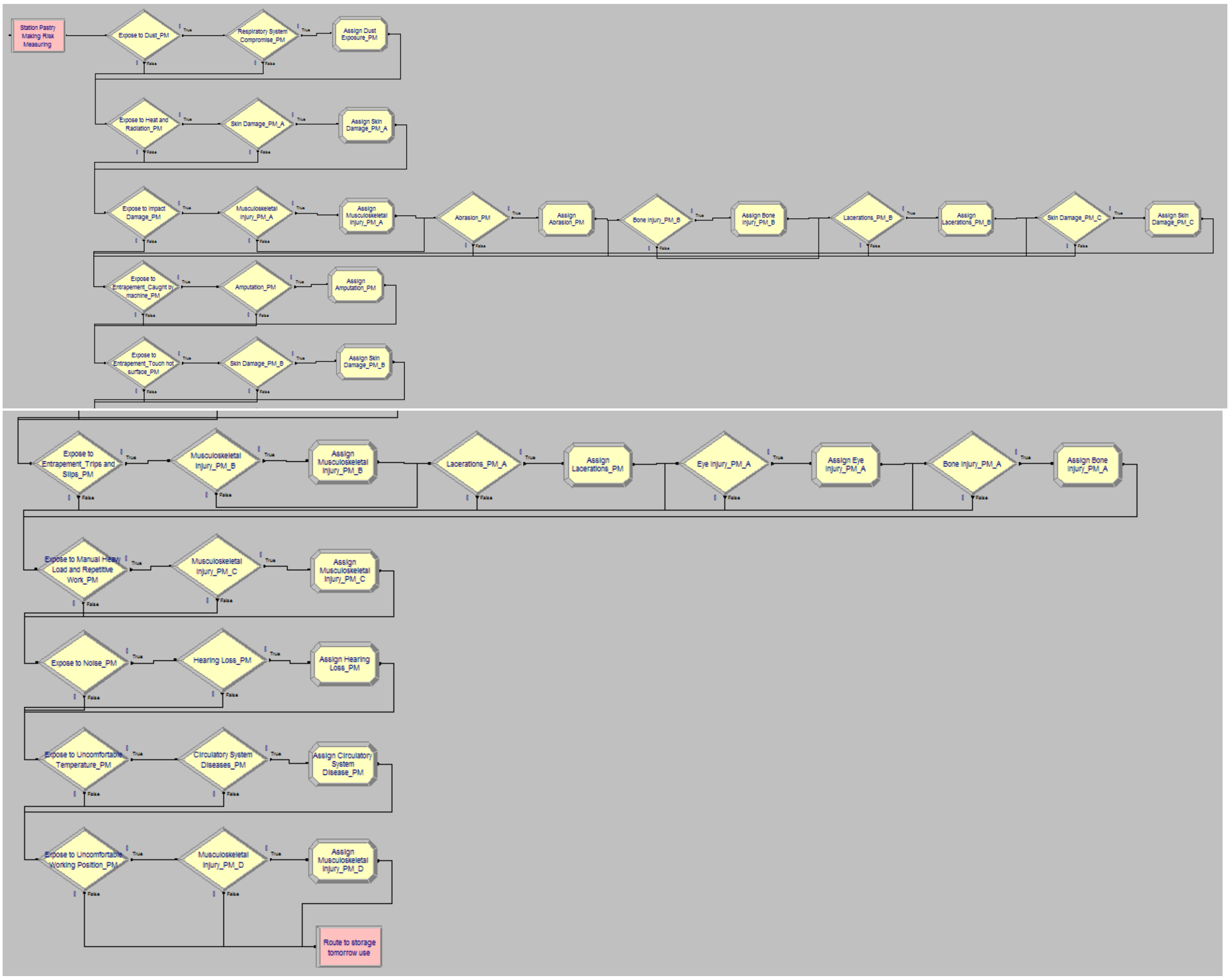


4. Simulation for the Bakery Industry Case

(1). Operation Simulation



(2). DQL risk modelling, pastry making process



Appendix D: Ethics Approval

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2019/28/LR-PS

19 August 2019

Zuzhen Ji
Mechanical Engineering
UNIVERSITY OF CANTERBURY

Dear Zuzhen

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Simultaneous Optimisation of H&S and Plant Layout Productivity".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 14th August 2019.

With best wishes for your project.

Yours sincerely

Dr Dean Sutherland
Chair, Human Ethics Committee